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Measuring Oman's Food Security Outlook for Crisis Aversion

by

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MEASURING OMAN'S FOOD SECURITY OUTLOOK FOR CRISIS AVERSION

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Abstract

Insecurity of food and water supplies in the Arabian Gulf is an important concern for stability in the region, where national security policy and food security policy interrelate. Even with three wars in Libya, Yemen, and Syria and several government overthrows in 2011—a year marked by doubled world grain prices—Arabian Gulf nations, other than Qatar, appear hesitant to publically declare the severity of impending food and water insecurity. In Oman, population growth at 4.98% between 2003 and 2013, an expatriate community comprising 44% of the total population, salinization issues and sinking groundwater tables, rising obesity, a culture of overindulgence, an overreliance on imported food, and instability in the international marketplace threaten the adequacy of the food and water supply.

This project endeavors to quantify the sensitivity of Oman's food security strategy to various shocks with a Bayesian belief network (BBN). A BBN is a model that estimates changes in conditional probability, given assumptions about the causal relationships between variables. In this present study, the probability that the daily energy supply (DES) exceeds a healthy lower bound, estimated at 2100 kilocalories/person/day, serves as the primary output of the BBN. The inputs to the BBN are eighteen variables organized into four categories: energy, trade, domestic agriculture, and human factors. Statistical analyses connect each of these input variables to historical effects on the output variable, DES.

The BBN is then used to test the sensitivity of DES in possible future scenarios. Example scenarios include (1) an international refusal to sell cereals to Oman, (2) a plummet in the price of oil, and (3) the mass emigration of the expatriate workforce from Oman. By focusing on DES, the model meets the standard international definition of a food secure nation and provides an indication of how possible future events could affect the food security of Oman. Beyond the specific model results, this effort also serves as a template and model for building future studies that could help identify—and avert—crises before they happen.

Keywords: Food Security, Oman, Bayesian Belief Network

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I. Motivation for the Project

Food security is a critical issue in the Arabian Gulf, where national security must meet the challenge of providing a strong food, water, and energy nexus. When grain prices more than doubled in 2011, government overthrows occurred in Tunisia, Egypt, and Libya, accompanied by civil uprisings in Yemen, Syria, and Bahrain.¹ While Oman will likely not have a character like Mohamed Bouazizi, the street vendor who lit himself on fire in Tunisia, serve as the ignition point between food security and national security, the stability of Oman's government and food supply will remain intricately tied.² In exploring this relationship, this project develops a model to measure the effects of crises that threaten Oman's minimum threshold of food and water supplies. Using a Bayesian belief network, the model quantifies Oman's sensitivity to changes in eighteen variables that affect food security.

The research question in this Trident project requires specification, and it takes on the following form: What variables most affect Oman's sensitivity to food insecurity? This thesis attempts to bridge a current gap in political science research between statistical analysis and the qualitative reality of food security; this project takes some of the initial steps in bringing measurable, calculated threat assessment into food and national security policy. Given the complex array of variables that affect food security, this Trident project offers a hypothesis based off the four categories of variables outlined in this paper: (1) Energy, (2) Domestic Agriculture, (3) Trade, and (4) Human Factors. The Bayesian belief network includes eighteen variables in total. When a category's variables adopt different discrete outcomes, changes occur in the probability distribution for the average Daily Energy Supply (DES) variable, estimated with a lower bound 2100 kilocalories/person/day, and a greater difference between the final and initial distributions indicates a higher sensitivity. In this framework, this Trident project offers the following hypothesis: With the heavy reliance on imports and strategic food storage in Oman, the Trade category will trigger the most variability in the probability distribution for average Daily Energy Supply.

Developing the methodology in this study is one of the major motivations and deliverables of this project. The conversation on food security in the Arabian Gulf exists, but the local research remains fixated on qualitative policy. Some data collection has occurred, but aside from Qatar's National Food Security Programme, no Arabian Gulf nation has publically generated any sort of metric to estimate food security needs.³ With this in mind, this Trident project brings approaches to the food security discussion that differ from Arab perspectives; it offers an important first step in building quantitative-based knowledge. Quantitatively, the Bayesian belief network (BBN) provides a metric for crisis aversion. Qualitatively, this project strives to inform policymakers of the relative risks associated with variables that affect food security in the region; while this research may not change Omani policy or predict threats with total accuracy, the Bayesian belief network methodology could assist Arabian Gulf officials with decision making. Because Arabian Gulf nations sometimes view the West as utilizing food security as a "political weapon," or an excuse to exert economic and political control over the

¹ Christian Parenti, "When Food Shortages Mean War," Salon, July 19, 2011, http://www.salon.com/2011/07/19/food_shortage_politics/ (accessed December 10, 2013).

² Rania Abouzeid, "Bouazizi: the Man Who Set Himself and Tunisia on Fire," Time, January 21, 2011, <http://www.time.com/time/magazine/article/0,9171,2044723,00.html> (accessed February 9, 2015).

³ Victoria Scott, "Advisor: Qatar's Food Security Plans Not Being Scaled Back," Doha News, February 13, 2014, <http://dohanews.co/advisor-qatars-food-security-plans-not-being-scaled-back> (accessed February 10, 2015).

Gulf, quantitative research may help depoliticize this critical issue.⁴ The Bayesian belief network may offer a more objective approach to risk assessment and national security decisions.

The Bayesian tool developed in this study serves as a first-run model; after running iterations in the future based off of new data, the model will adjust and become more accurate over time. Despite anticipated flaws in accuracy, from a political science perspective this Trident project proves critical since it develops new methodologies, and these methodologies may someday help bring objective analysis to food security issues. The resulting recommendations for crisis aversion developed in this project could encourage stability in Arabian Gulf regimes, which serve as the home of the United States Navy's Fifth Fleet. Oman serves as an interesting, capable starting point for food security risk analysis.

a. The Importance of Oman

The nation of focus, Oman, has a history of international trade, an advantageous geographic location, a potential for agricultural production and fishing, and a strategic food storage system that make it suitable for a food security model. Oman served as a gateway to the East under Portuguese control from 1508 until the Ottoman Empire took over in 1659. The Ottoman Turks continued this trend of international trade, as did Ahmad ibn Said of Yemen after ousting the Ottomans in 1741 and founding the current royal family.⁵ With the beginning of close ties to Great Britain in the 18th century, Oman became an economic power, controlling parts of Zanzibar, Baluchistan, and Iran. In the 19th and 20th centuries, Oman lost these holdings and dealt with rebels from its interior; the Ibadi sect from Nizwa wanted to overthrow the sultan in Muscat, so the Treaty of Seeb gave the Imam of Oman, the rebels' religious leader, autonomy in interior regions. Conflict ignited again in 1954, but the rebels lost, partly due to British aid. The sultan terminated the Treaty of Seeb in 1959, and in 1964, another separatist movement began with the Dhofar Liberation Front, backed by communist governments. The coup by Sultan Qaboos bin Said in 1970 gave way to economic rebirth, rapid modernization, and a fierce effort to stifle the Dhofar insurgency. Since then, Oman has maintained a moderate foreign policy and joined the United Nations, Arab League, and Gulf Cooperation Council (GCC).⁶ While Omanis staged some protests during the Arab Spring in 2011, the campaigns focused on reform rather than deposing the sultan, and Qaboos subsequently granted increased unemployment benefits as well as more powers to the Majlis al-Shura.⁷ However, Oman could lose political stability in another food price spike, so it remains concerned about food security crises.

Plagued with the same problems as many Arabian Gulf countries, Oman could lead regional food security reform. A heavy reliance on imports, annual population growth at 4.98% between 2003 and 2013, an expatriate community comprising 44% of the total population in 2013, salinization and sinking groundwater tables, overgrazing by camels and livestock, threats from pirates, the Syrian crisis, and the Islamic State, and adult obesity and child malnutrition — themes resonating throughout GCC nations—all plague Oman.⁸ In the future, Oman's location as

⁴ Mohammed Hamza, "الأمن الغذائي العربي.. بين النظرية والتطبيق" (Arab Food Security: Between Theory and Practice)," *Oman Daily Observer*, April 7, 2013, <http://main.omandaily.om/?p=24757> (accessed February 4, 2014).

⁵ Royal Navy of Oman, "Maritime History of Oman," Royal Navy of Oman, <http://rno.gov.om/English/Topics/About/History.php> (accessed December 15, 2013).

⁶ Joseph Kechichian, *Oman and the World* (California, RAND, 1995), Chapter 9.

⁷ James Worrall, "Oman: The Forgotten Corner of the Arab Spring," *Middle East Policy* 19, no. 3 (2012), <http://onlinelibrary.wiley.com/doi/10.1111/j.1475-4967.2012.00550.x/full> (accessed November 29, 2013).

⁸ National Center for Statistics and Information, "Economic Review Q2 2013," Sultanate of Oman, http://www.ncsi.gov.om/NCsi_website/viewPublication.aspx?id=1940 (accessed November 29, 2013).

the gateway to the Strait of Hormuz, varied climate, relatively large expanse of unused land, aquaculture resources, and impressive strategic storage system could make the nation a regional leader in food security. However, Oman will need to generate a strategy for food and water accumulation to compensate for potential environmental, political, and economic crises.

Currently, expatriates in Oman eat little and provide the blue-collar foundation to the economy. At the same time, Omani nationals tend to eat more, become obese, and die earlier.⁹ So while many Omanis maintain well-fed consumption patterns, they should consider adopting sustainably-fed consumption patterns to ensure enough food for them and the expatriates in the future. Neglecting the workforce could encourage net migration or limit efficiency, undermining Oman's economic stability and ability to procure food. Omanis will hopefully embrace the methodology from this project and use the statistics to re-educate Omanis about potential crises.

b. The Connection between Food Security and National Security

According to the 2001 edition of the Food and Agriculture Organization (FAO) "The State of Food Insecurity in the World" report, "Food Security exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life."¹⁰ Given the focus on Oman in this Trident project, it seems appropriate to generate a definition of food security catered to Oman's specific needs. According to this project, Oman must satisfy four conditions to become food and water secure: (1) provide enough food for all 3.876 million people in Oman, especially ensuring the health and sufficient caloric intake of the at-risk expatriate workforce; (2) determine the appropriate amount of domestic agricultural production; (3) protect imported foods from international price spikes and crises; and (4) utilize the energy infrastructure as the foundation for food security. In keeping with these observations, this study will approach the available data by summarizing the four conditions into categories: (1) Human Factors, (2) Domestic Agriculture, (3) Trade, and (4) Energy.

Categorizing and evaluating the relative impact of these variables is important because food security has become tied to national security. In the past, these entities were typically considered unrelated, but today food security constitutes a non-military threat to the welfare of the nation-state. The survival of the nation comes into question in the extreme case of zero availability and access to food and water. More realistically, food security can "drastically reduce the welfare of the nation in a fashion that requires a centrally coordinated national mobilization of resources to mitigate or reverse."¹¹ Many Arabian Gulf nations express a sense of national vulnerability in regards to the lack of water and food availability, an indicator that they consider the food and water crises part of their national security strategies; their strategic reserves of food and water serve as tangible evidence of their concern. Particularly in the Arabian Gulf, political unrest, as witnessed during the Arab Spring, threatens to erupt when food and water availability decreases, and migration could result from shortages and cripple economic production. Since Arabian Gulf nations do not produce sufficient food domestically, foreign

⁹ World Health Organization, "Global Database on Body Mass Index," Detailed Country Data, 2014, <http://apps.who.int/bmi/index.jsp> (accessed November 24, 2014).

¹⁰ Hartwig de Haen and others, "The State of Food Insecurity in the World," Food and Agriculture Organization Economic and Social Development Department, <http://www.fao.org/economic/en/#.UtNbmdJDtgg> (accessed December 02, 2013).

¹¹ Paul Smith, "Food Security and Political Stability," *Asia-Pacific Center for Security Studies*, September 11, 1998, http://www.apcss.org/Publications/Report_Food_Security_98.html (accessed Feb 4, 2014).

nations could also utilize food as a weapon against Oman, as a means of political influence. Given these concerns, food security has become a matter of regime survival in the Arabian Gulf.

Food insecurity appears in a complex, dire form in the Middle East. A combination of rapid population growth, arid climate, and government mismanagement has led to failing agricultural sectors and economic vulnerability.¹² Today, most Arab nations import between 50% and 90% of the food they consume, and the region serves as the largest net importer of cereals in the world. Over the next twenty years, dependence on imports is projected to increase by 64%.¹³ Furthermore, international producers of wheat and rice consume most of their domestically produced cereals, so only 18% and 6% respectively of these crops' total global production is exported. In this thin market, small shifts in supply or demand generate large price shifts, and state-owned monopolies dominate cereal exports.¹⁴

Before 2008 Arabian Gulf states believed their oil wealth could overcome any food price spike. That year, however, these nations discovered that the food market is not as deep or liquid as the oil market, and cereals became unavailable as suppliers refused to sell; at the time, there were record grain harvests and at least 1.5 times as much food as the world demanded.¹⁵ However, the wealthiest 20% of the population consumed 80% of the world's production, and suppliers exercised caution in selling to the rest of the world. Although the FAO noted a 45% increase in the world food price index between August 2007 and May 2008, grain suppliers became reluctant to sell due to droughts in the 2005 and 2006 that spurred low grain reserves, less than 54 days-worth globally.¹⁶ Suppliers also diverted 5% of the world's cereals to lucrative agrofuels. Aside from these short-term causes, the 2008 crisis revealed long-term issues like concentrated ownership of grain production, unfair trade agreements, and the diminishing opportunity for poor countries to determine their own food security policies.¹⁷ The 2008 food price spike lessened after export bans relaxed and the global economy collapsed later that year, but many of the underlying problems remained.¹⁸ It became apparent that food availability—not price—would become the key issue for Arabian Gulf nations.

Despite the 2008 crisis and the political upheaval wrought by the Arab Spring, many Arabian Gulf nations with surviving monarchies have not implemented food security into their national security strategies. Drought, wild fires, and government directives in Russia and the Ukraine caused the spike that nearly doubled the price of wheat between late 2010 to early 2011. During the same time, Tunisia, Egypt, Libya, and other Arab nations burst into protest, and two civil wars in Yemen and Syria continue today.¹⁹ While international organizations and non-governmental organizations like the World Bank and GRAIN have subsequently formulated an agricultural perspective on food security, political science has many unanswered questions when

¹² Abdulhaleq Abdulla, "Contemporary Socio-Political Issues of the Arab Gulf Moment," The Centre for the Study of Global Governance at the London School of Economics, September 2010, Number 11, <http://www.lse.ac.uk/middleEastCentre/kuwait/documents/paperabdulla.pdf> (accessed March 1, 2015).

¹³ Qatar's National Food Security Programme, "The Global Food Crisis: Middle Eastern Dimensions," Qatar's National Food Security Plan, <http://www.qnfs.gov.qa/about-us> (accessed December 2, 2013).

¹⁴ Corazon Aragon, Flordeliza Lantican, and Eden Piadozo, "The United Nations Must Manage a Global Food Reserve," *UN Chronicle* 45, no.2 (2008), <http://unchronicle.un.org/article/united-nations-must-manage-global-food-reserve/> (accessed December 03, 2013).

¹⁵ Anup Shah, "Global Food Crisis 2008," *Global Issues*, August 10, 2008, <http://www.globalissues.org/article/758/global-food-crisis-2008> (accessed December 3, 2014).

¹⁶ Ibid.

¹⁷ Ibid.

¹⁸ Anuradha Mittal, "The 2008 Food Price Crisis: Rethinking Food Security Policies," *G-24 Discussion Paper Series* no. 56 (2009), http://unctad.org/en/docs/gdsmdpg2420093_en.pdf (accessed December 10, 2013).

¹⁹ Parenti, "When Food Shortages Mean War."

translating food security into national security. Additionally, concern for Africa today largely overshadows Middle Eastern food, water, and energy issues in discussions of international politics; for instance, the Peace Corps Food Security program only exists in Mali, Armenia, and Tonga.²⁰ Consequently, a large gap in research exists in developing a food security model suited for Arabian Gulf environments. This gap represents a huge hole in national security policy.

c. Previous Studies and Datasets

Few Western publications offer a comprehensive outlook of Oman's unique food security outlook. One useful piece for this study, though, is the *Phase 1 Report: Study to Develop Food Security Strategy and Master Plan for the Sultanate of Oman* from GRM International. This study prioritizes food commodities consumed in Oman based off the energy levels they provide per person per day in Oman, and GRM International labels these foods as the "Basic Commodity Food Basket." The commodities rank as follows: rice, flour, wheat, vegetable oil, fruits, sugar products, fish and seafood, poultry, red meat, dairy products, and legumes. The GRM study then goes on to measure the price volatility of each product over the past twenty years using standard deviation, and it also lists by percentage the nations that export each crop to Oman.²¹ While this study comes from 2010 and therefore needs updated data, it provides the basic model for analyzing prices of strategic crops and calculating the impact of insufficient imports.

In regards to generating a model for food security, Qatar is the only nation in the Arabian Gulf that has a partially publicized national plan, and that project appears to be the only one comparable to this Trident project; other nations may have plans, but much of the information for food security remains classified.²² Qatar's National Food Security Programme (QNFSP) began in 2008 in an attempt to diminish reliance on imports, creating a model in 2011 with several scenarios for Qatar to supply between 40% and 90% of its domestic demand for food. In 2014, QNFSP recommended the 40% scenario to the Qatari government, but the entire document will not be published due to security reasons.²³ Regardless, QNFSP likely did not employ a Bayesian belief network, but the type of model used is not verifiable.

Bayesian belief networks and distributions have, however, been utilized in projects with interdisciplinary influence, as outlined in the book *Bayesian Inference in the Social Sciences*.²⁴ For example, Xun Pang modeled the relationship between ethnic minority rule and civil war, finding that the probability distribution moves, across several model scenarios, towards civil war when nations have ethnic minority rule.²⁵ As this study demonstrates, Bayesian methodologies are applicable in the social sciences.

When finding datasets pertinent to food security for this project's Bayesian belief network, the World Bank's World Development Indicators (WDI) and the United Nations' Food and Agriculture Organization (FAO) provided extensive, diverse quantitative information.²⁶ In

²⁰ Peace Corps, "Food Security," Peace Corps, <http://www.peacecorps.gov/volunteer/learn/whatvol/foodsecurity/> (accessed November 29, 2013).

²¹ GRM International, "Phase 1 Report: Study to Develop Food Security Strategy and Master Plan for the Sultanate of Oman," *Sultanate of Oman's Authority for Stores and Food Reserve* (2010).

²² Scott, "Advisor: Qatar's Food Security Plans Not Being Scaled Back."

²³ Ibid.

²⁴ Ivan Jeliazkov and Xin-She Yang, *Bayesian Inference in the Social Sciences* (Hoboken: John Wiley & Sons, 2014).

²⁵ Ibid., 58

²⁶ Food and Agriculture Organization of the United Nations, "Food Security Indicators," Food and Agriculture Organization of the United Nations, <http://www.fao.org/economic/ess/ess-fs/ess-fadata/en/#.UtOYntJDtgg> (accessed November 29, 2013).

these sources, the pertinent variables had data from at least 1970 until 2012.²⁷ Accordingly, sufficient quantitative sources of data were available for this study, and the Intergovernmental Panel on Climate Change AR5 and FAOSTAT provided additional information on climate change and on production and trade respectively.²⁸ Furthermore, the study included other datasets from sources like the U.S Energy Information Association (EIA), the U.S. Department of Agriculture (USDA), the National Oceanic and Atmospheric Administration (NOAA), and AquaStat. By adding a quantitative aspect to the qualitative information provided by available publications, newspapers, interviews, and conferences, the existing literature and datasets helped generate measurements for Oman's potential food security crises.

d. Choice of Methodology

A number of different modeling techniques could be applied in analyzing Oman's food security threats, but the Bayesian belief network is most suited for this study. Black box multiple regression and ad hoc structured models were the two alternative choices, but they proved more limited than Bayesian belief networks. There are numerous problems with multiple regression, which is linear only and considers all the predictor variables at once; the calculations would become too complex and time-consuming, given the large amount of variables involved in food security. High dimensionality complicates this kind of model. Additionally, multiple regression does not address causality in the relationship between independent variables and the dependent variable, and multicollinearity among variables can easily distort the output. While a black box multiple regression model is hugely limited by linearity, an ad hoc structured model does not provide enough organization. Although causality among variables is explored in a logically structured network, the disparate variables are not measured in the same units, and it becomes difficult to measure the effect of one variable on the next.

With these limitations in mind, a Bayesian belief network proves better than the two aforementioned models. As a nonlinear model that focuses in on small clusters of nodes, the Bayesian structure combats the high dimensionality that occurs when multiple regression uses large numbers of variables. In comparison to ad hoc structured models, the Bayesian belief network better relates variables through conditional probabilities, accounting for the possibility that the variables have different units; the model translates the data for each variable into a distribution curve to achieve this purpose. Accordingly, Bayesian belief networks have proved useful in modeling extremely complex functions, and they perform relatively well when working with unknown or distorted inputs.

II. Considerations for the Bayesian Belief Network

Bayesian belief networks simulate the world through a compilation of connected conditional probabilities. The Bayesian belief network recognizes that some conditions become more likely when others have occurred. Each node in the models represents a random variable,

²⁷ The World Bank, "Oman: Data," The World Bank Development Indicators, 2015, <http://data.worldbank.org/country/oman> (accessed March 11, 2015).

²⁸ Intergovernmental Panel on Climate Change Working Group I, "Fifth Assessment Report of the Intergovernmental Panel on Climate Change," *The Physical Science Basis* 12, no. 9 (2013), http://www.climatechange2013.org/images/uploads/WGIAR5_WGI-12Doc2b_FinalDraft_All.pdf (accessed December 18, 2013).

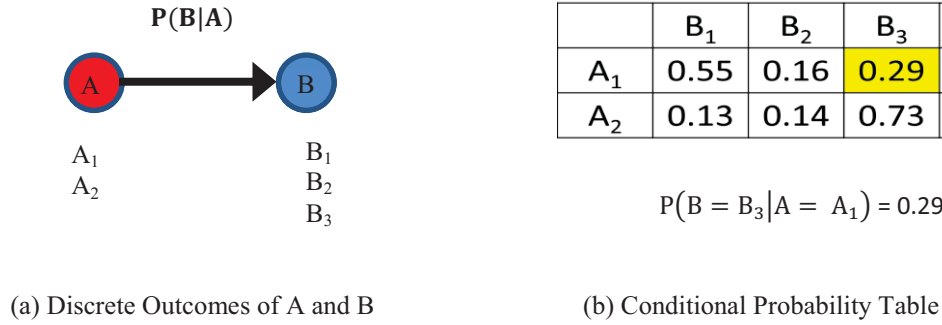


Figure 1. Bayesian Basic Network

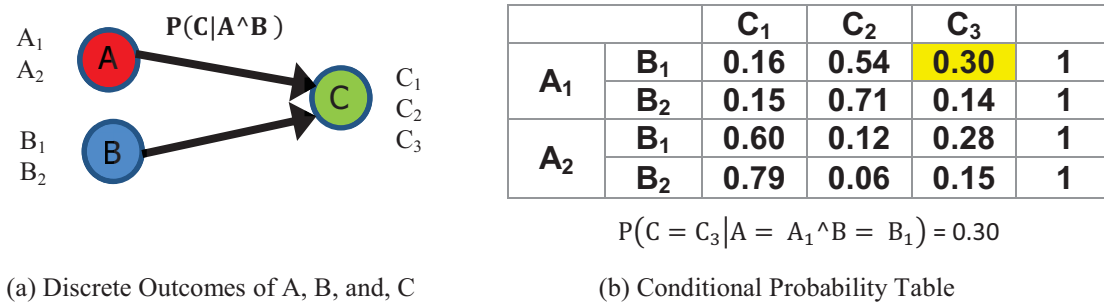


Figure 2. Three-Node Network

and the arrows connecting the variables represent conditional probabilistic relationships.²⁹

a. Bayesian Belief Network Basics

The example in Figure 1 is a simple version of a Bayesian belief network containing two related variables, A and B. The variable A has two possible states, A₁ and A₂, while the variable B has three possible outcomes, B₁, B₂, and B₃. The network on the left depicts how the outcomes of B relate to the outcomes of A, but the table on the right shows how to determine the probability of a certain state of B (B₃) occurring, given a specific state of A (A₁). In these types of tables, the probabilities listed in each row must add up to 1; one of the three states of B must occur after either A₁ or A₂ transpires. This premise holds true for Bayesian belief networks with more than two variables as well.

The network in Figure 2 has three related variables. The general equation for the diagram describes the overall probability of the outcomes of C, given the outcomes A and B. In order to generate a table to consider specific outcomes of A, B, and C, similar to the one in Figure 1, the table must become three dimensional to account for all the possible combinations of the three variables. The table (2b) depicts the probability of the C₃ outcome given the A₁ and B₁ states.

The primary advantage of a Bayesian belief network is that its structure creates efficiencies in both representation and computation. If, for example, there were 100 factors governing a phenomenon, then a conditional probability table describing the scenario, $P(O|A_1 \wedge A_2 \wedge A_3 \wedge \dots \wedge A_{100})$, would have 100 dimensions. This table would be too large for

²⁹ Judea Pearl, *Probabilistic Reasoning in Intelligent Systems: Networks of Plausible Inference*. (New York: Morgan Kaufmann, 2014).

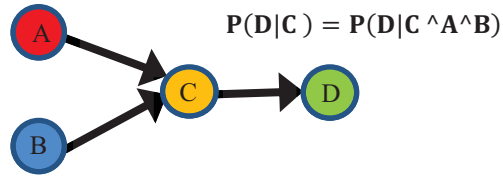


Figure 3. Simplifying the Network

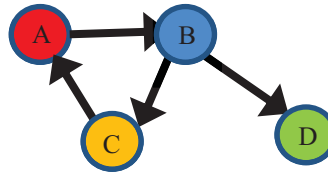


Figure 4. Illegal Cycle in the Network

computation and storage, and there would likely be an insufficient amount of data to populate the entries. A Bayesian belief network, however, has independencies between factors that reduce the one large table to multiple, much smaller tables. As shown in Figure 3, once the value for a particular variable becomes known, the nodes prior to that variable's node do not matter in regards to future nodes, unless connected to them by a different path. A and B have already affected C, and their initial effect will translate through C into D. Therefore, when determining the probability of D given C, the network can simplify down into a two-node network, similar to the example in Figure 1. Instead of calculating the probabilities of specific states of A, B, C, and D in a four-dimensional table, the Bayesian belief network simplifies into a two-dimensional table relating only the parent node C and the child node D. In this case, conditional independence is established because $P(D|C) = P(D|C \wedge A \wedge B)$. It should be noted that information also flows upstream if a value is known downstream. If the outcome of C is fixed in the original network without knowing A and B, the probability distributions for the outcomes of A and B will change.

Bayesian belief nets exhibit other characteristics that keep the calculations of probabilities manageable. In order to prevent the probabilities from spiraling around indefinitely, no cycles are permitted. An example of a cycle is provided in Figure 4, where a change in A would affect the probability of B and subsequently C. Since C cycles back to A, the changes in C would then alter the value at A's node. The change at A's node would propagate out through the network until C alters A's value again. Accordingly, changes in probability would spiral around the A-B-C loop. With this indefinite cycling in mind, the constraint on cycles demands careful consideration when building the network, but clear causality makes for better networks.³⁰

The rule that prohibits cycles ensures quick updates and recalculations when values change in the model.³¹ The probabilities in the network will adjust automatically to modifications in data. Changes propagate in the forward and backward directions through the model, quantifiably update the other beliefs, and formulate more accurate conclusions; as one phenomenon increases in probability, a competing possible cause must decrease in probability.

³⁰ Marek Druzdzal and Herbert A. Simon, "Causality in Bayesian Belief Networks," *Proceedings of the Ninth International Conference on Uncertainty in Artificial Intelligence* (New York: Morgan Kaufmann Publishers Inc., 1993).

³¹ Norsys Software Corporation, "Netica Tutorial," Norsys Software Corporation, http://www.norsys.com/tutorials/netica/nt_toc_A.htm (accessed December 18, 2013).

Thus, competing probabilities explain each other away as their values change. By supplying evidence of past events, the Bayesian belief network can use competing probabilities to predict future outcomes and model reality.³² With the available data on variables that affect Oman's food security, the equation for this project's network was $P(\text{Food Security in Oman} \mid \text{Available Data})$.

b. Challenges of Network Construction

When constructing the food security Bayesian belief network and compiling datasets for the variables, the question arose of how to assign specific outcomes to each variable. The process of dividing a variable's data points into states is known as binning; each state receives a designated range of values within the dataset. Although the dataset could be binned to optimize the distribution of data points in each state, this approach is not ideal because the split points are artificial. A better option involved using split points with significance in the current food security environment. To further simplify the binning process and keep the dimensionality of each probability table relatively small, this project limited the number of states per variable to three.

The decision to limit the number of outcomes per variable helped avoid the instance where a probability table lacked a certain combinations of states. For instance, if two connected nodes each had three states, the conditional probability table would have nine possible combinations; if each dataset had only 43 annual points from Oman for the years 1970 to 2012, some of the nine combinations may not have occurred over the course of those 43 years. This problem is called the smoothing problem.

In order to increase the number of data points and diminish the number of unmet combination, this study implemented data from other Arabian Gulf nations. This is known as back-off smoothing. For each variable included in the Bayesian belief network, data for the United Arab Emirates, Saudi Arabia, and Kuwait was also utilized; these nations were selected because, aside from Oman, they were the only Arabian Gulf nations in FAOSTAT's datasets. Rather than viewing these datasets as representations of other nations, though, they should instead be perceived as potential future states for Oman; these states are plausible because they are proven to have occurred in the past for other countries in the Arabian Gulf environment.

When selecting the variables to include, a plethora of nodes would diminish the impact of each node in regards to changes in the final node's value. Including many nodes for closely related variables would also potentially distort their appropriate impact on the final node, and it would be difficult to determine the proper direction of causality. Instead, this project endeavored to include fewer variables in order to illustrate clear causality between the variables. Starting with average Daily Energy Supply (DES) as the final node of the Bayesian belief network, the network grew according to the four categories that corresponded with Oman's four conditions for food and water security: Human Factors, Trade, Domestic Agriculture, and Energy.

c. Selecting the Final Node

The choice of average DES as the final node of the Bayesian belief network—and thus as the main criterion for food security—requires further explanation. Return first to the FAO's definition of food security: "Food security exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food to meet their dietary needs and

³² Mark Krieg, *A Tutorial on Bayesian Belief Networks* (Edinburgh: DSTO Electronics and Surveillance Research Laboratory, 2001), <http://www.dsto.defence.gov.au/publications/2424/DSTO-TN-0403.pdf> (accessed December 19, 2013).

food preferences for an active and healthy life.”³³ In order to consistently maintain a healthy daily energy supply, individuals require stable access to nutritious foods. Furthermore, meeting daily standards for energy supply enables both expatriates and nationals in Oman to perform necessary tasks in an active lifestyle. Consequently, average DES meets the FAO definition’s demands for access and a healthy life. By averaging out the daily energy supply of all Oman’s inhabitants, too, the threshold set for DES will indicate whether or not a satisfactory portion of the population has become food secure.

In determining the minimum threshold for daily energy supply for the Bayesian belief network, a study conducted by the FAO provided an initial estimation. In the “Updating the Minimum Dietary Energy Requirements” report, the FAO determined an overall minimum daily dietary energy requirement by “aggregating sex-age requirements weighted by the proportion of each sex and age group in the total population...[for] the estimated country birth rate for a hypothetical country in 1999-2001.”³⁴ The result came out as 1680 Kcal/person/day. This threshold, however, indicates the baseline energy supply to avoid undernourishment in any hypothetical country.

A value more specific to Oman seemed appropriate; Omanis enjoy a high standard of living due to revenues from oil and natural gas, so they consequently have become accustomed to choosing which foods to consume. When studying eating and drinking habits through the 2001 Household Expenditure and Income Survey, the Ministry of Health in Oman concluded that the nation’s average DES hovers around 2281 Kcal/person/day when including children, but consideration of solely adults yields a daily energy supply of 2620 Kcal/person/day.³⁵ Regardless, these daily energy supply levels reflect a population unconcerned with food shortages, so the aforementioned GRM International report attempted to find the minimum comfortable level of DES best suited for Oman. The report notes that Omanis begin to use more energy than provided by their food when they fall under the 2000 Kcal/person/day mark. Malnutrition arises between 1500 and 1900 Kcal/person/per day, first for large men performing heavy labor, then growing adolescents, pregnant women, working women, and finally the remaining children. But to maintain a comfortable daily energy supply, also containing 63-70 grams/person/day of protein and 70-78 grams/person/day of fat, the GRM International report promotes a goal DES no lower than 2100 Kcal/person/day.³⁶ Since the research in this Trident project hopes to generate long-term plan to maintain minimum levels of food security, the GRM International report’s lower bound DES of 2100 Kcal/person/day will serve as the lowest split point in the Bayesian belief network’s final node.

III. Constructing the Bayesian Belief Network

The Bayesian belief network consists of eighteen nodes, corresponding to the eighteen variables considered. This section presents each variable in three portions:

³³ Hartwig de Haen and others, “The State of Food Insecurity in the World.”

³⁴ Food and Agriculture Organization Statistics Division, “Updating the Minimum Dietary Energy Requirements,” *FAO Methodology for the Measurement of Food Deprivation* (2008), 8, http://www.fao.org/fileadmin/templates/ess/documents/food_security_statistics/metadata/undernourishment_methodology.pdf (accessed December 18, 2013).

³⁵ Deena Alasfoor, Hanadi Rajab, Buthaina Al-Rassasi, “Food Based Dietary Guidelines: Technical Background and Description,” *Task Force for the Development and Implementation of the Omani Food Based Dietary Guidelines* (2008), 57 - 77, <http://www.fao.org/ag/humannutrition/19542-0561250979706400b7cc8ca7366cc07c0.pdf> (accessed December 19, 2013).

³⁶ GRM International, “Phase 1 Report,” 11-12.

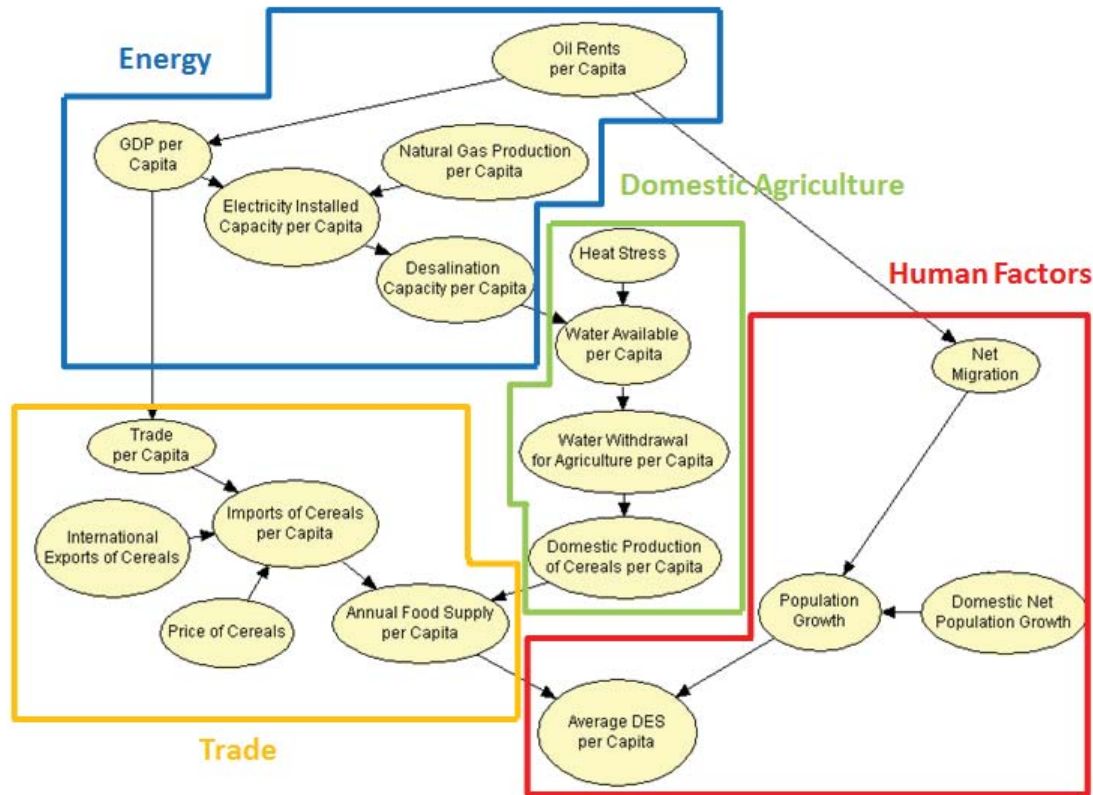


Figure 5. Full Bayesian Belief Network with Categorization

(1) establishing the causal relationships of the node to its surrounding nodes, (2) defining the dataset and binning the variable, and (3) presenting the conditional probabilities for the node, where each column in the conditional probability tables sums to 1. The variables are clustered by the four aforementioned categories: (1) Energy, (2) Trade, (3) Domestic Agriculture, and (4) Human factors. The entire network is presented in Figure 5 with categorization.

1. Energy Nodes

a. Oil Rents per Capita

In relation to the energy variables in Figure 6, oil rents per capita—defined as “the difference between the value of crude oil production at world prices and total costs of production”—impact two child nodes: GDP per capita and net migration.³⁷ Oil rents are similar to revenues, but they account for all the associated costs, too. In regards to Gross Domestic Product (GDP), Oman’s oil production accounts for 37.2% of the country’s GDP, and this relationship has remained strong throughout Oman’s history.³⁸ Furthermore, Oman is considered a rentier state, wherein “rent”—in this case oil—“enters into the composition of the price of commodities in a different way from wages and profit...and is generally a reward for

³⁷ The World Bank, “Oil Rents,” The World Bank Development Indicators, 2015, <http://data.worldbank.org/indicator/NY.GDP.PETR.RT.ZS> (accessed November 20, 2014).

³⁸ Ibid.

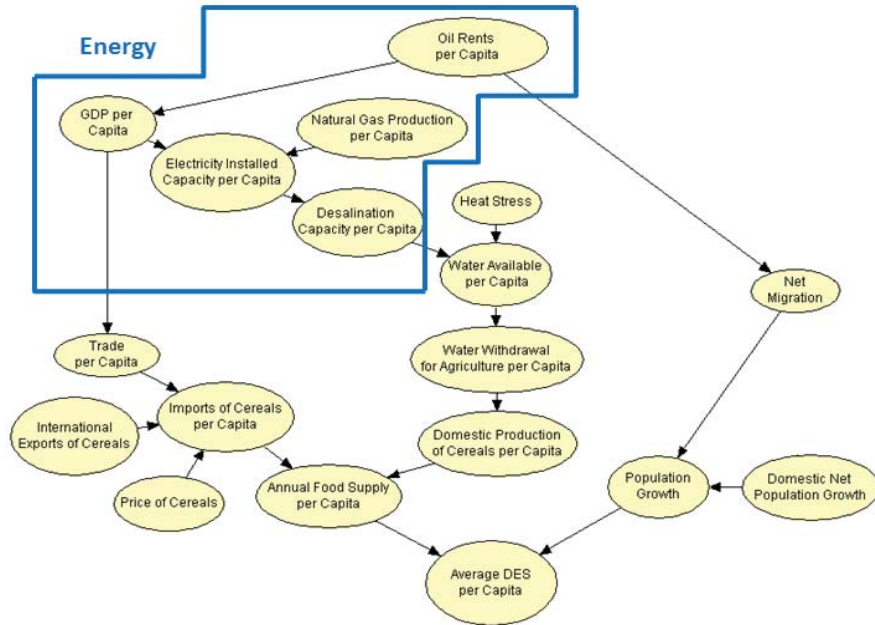


Figure 6. The Five Energy Variables

ownership of all natural resources.”³⁹ In other words, Oman’s economic vitality depends on the resources within its territory and the revenues, in this case oil rents, earned from them. As for the net migration node, Middle Eastern dictatorships defy the general trend for non-democracies, which typically have more migrants leave than enter; instead oil-rich Gulf states, which have the largest variation in net migration in the world, attract more migrants for entrance than exit. This phenomenon is largely based on the availability of oil revenues and the opportunity for work among the small domestic population.⁴⁰

The World Bank provided the data for the oil rents per capita variable, converted from percent of GDP to constant 2005 U.S. dollars per capita by multiplying the original data by GDP per capita (in constant 2005 U.S. dollars).⁴¹ The data spanned from 1970 to 2012, a total of 43 years, for the four countries: Oman, the United Arab Emirates, Saudi Arabia, and Kuwait. This compilation of information produced 172 data points. Three bins were applied to this dataset, \$5,000 per capita as the lower split point and \$10,000 per capita as the higher split point. Because the oil rents per capita variable has a special role as the first parent node in the network, these split points were selected in order to generate a uniform probability distribution among its three bins. The emphasis on evenness is acceptable because these Arabian Gulf nations all fall in the same category of having high oil rents per capita relative to the rest of the world; Oman, for instance, produces more than twice as many barrels of oil per capita, 222.88 barrels per day per 1,000 people, than Canada or Venezuela.⁴²

³⁹Hazem Beblawi, “The Rentier State in the Arab World,” *Arab Studies Quarterly* Vol. 9, No. 4 (Fall 1987), 383

⁴⁰ Joseph Wright, “Exit During Crisis: How Openness, Migration, and Economic Crisis Affect Democratization,” Kellogg Institute, May 2010, <https://kellogg.nd.edu/publications/workingpapers/WPS/367.pdf> (accessed March 15, 2015).

⁴¹ U.S. Energy Information Administration, “Oman,” Independent Statistics & Analysis, October 10, 2013, <http://www.eia.gov/countries/country-data.cfm?fips=MU#pet> (accessed November 19, 2014)

⁴² NationMaster, “Oil Production per Capita: Countries Compared,” 2007, <http://www.nationmaster.com/country-info/stats/Energy/Oil/Production/Per-capita> (accessed March 12, 2015)

Oil Rents per Capita (Constant 2005 \$U.S. per Capita)	
State	Probability
<5000	0.331
(5000, 10000)	0.331
>10000	0.338

Figure 7. Prior Probability Table for Oil Rents per Capita

Since the oil production node lacked parent nodes, the prior probability distribution in Figure 7 was generated by dividing the number of cases per bin by 172, the number of data points.

b. GDP per Capita

Gross Domestic Product (GDP) per capita, preceded by the oil rents per capita parent node, connects down to the electricity installed capacity per capita node in the energy block and the trade per capita node in the trade block of nodes. The causal relationship between GDP per capita—“the sum of gross value added by all resident producers in the economy divided by midyear population”—and electricity installed capacity per capita represents the notion that a nation’s revenues can purchase durable infrastructure, like Oman’s Main Interconnected System (MIS) and the Salalah system of electrical grids.⁴³ In regards to the GDP and trade, the rise of income encourages the rise of global supply chains and an increase in the crossing of goods across borders.⁴⁴

The World Bank provided the GDP per capita in constant 2005 U.S. dollars for Oman, the United Arab Emirates, Saudi Arabia, and Kuwait for the years ranging from 1970 to 2012.⁴⁵ Represented in 172 data points, this variable consists of two bins. The bins were split by the \$22,818 per capita mark, the World Bank’s classification between a high income and upper middle income nation.⁴⁶

The first table in Figure 8a shows that most of the years (55.23%) in the dataset had a GDP per capita below \$22,818, in the upper middle income category, and Figure 8b displays the conditional probabilities distribution between oil rents per capita and GDP per capita.

⁴³ John Hartwick, “Oil Rents, Infrastructure Investment and Sustainable Development,” Center of Economic Research at ETH Zurich, 2010, http://www.cer.ethz.ch/sured_2010/keynote_lectures/SURED-10_Keynotes_Hartwick.pdf (accessed March 9, 2015)

⁴⁴ “GDP and Trade Growth,” *The Economist*, May 26, 2011, <http://www.economist.com/node/18744587> (accessed February 20, 2015)

⁴⁵ The World Bank, “Oman: Data.”

⁴⁶ “The Global Market and Developing Nations,” Pearson Education, 2015, <http://www.infoplease.com/cig/economics/production-income-classifications.html> (accessed March 2, 2015)

GDP per Capita (Constant 2005 \$U.S.)	
State	Probability
<22818	0.552
>22818	0.448

(a) Prior Probability Table

GDP per Capita (Constant 2005 \$U.S.)			
Oil Rents per Capita (Constant 2005 \$U.S.)	<5000	(5000, 10000)	>10000
<22818	0.930	0.561	0.172
>22818	0.070	0.439	0.828

(b) Conditional Probability Table

Figure 8. Tables for GDP per Capita

Natural Gas Production per Capita (Cubic Feet per Capita)	
State	Probability
<84000	0.318
>84000	0.682

Figure 9. Prior Probability Table for Natural Gas Production per Capita

c. Natural Gas Production per Capita

Natural gas production per capita has no parent nodes, but it links down to the electricity installed capacity per capita node. This causal relationship is supported by the fact that Oman produces electricity primarily from natural gas, although some diesel and distillate generation also occurs. Natural gas, though, provides 7.2 GW of Oman's 8.8 GW generating capacity. In the past, the rise in natural gas usage supported the doubling of Oman's electricity capacity between 2000 and 2010.⁴⁷

Natural gas production per capita, converted from billion cubic feet to cubic feet per capita, was documented by the U.S. Energy Information Administration.⁴⁸ The annually recorded data spanned from 1980 to 2012, a total of 33 years, for Oman, the United Arab Emirates, Saudi Arabia, and Kuwait. The 132 data points separated into two bins, divided by an 84,000 cubic feet per capita split point; this value was the average of the four countries' natural gas production per capita in the year 2000, when natural gas production became a major impetus for the increase in electricity capacity in the Middle East.⁴⁹

Because the natural gas production node lacked parent nodes, the probability distribution in Figure 9 was generated by dividing the number of cases per bin by 132, the number of data points.

⁴⁷ U.S. Energy Information Administration, "Oman."

⁴⁸ Ibid.

⁴⁹ Ibid.

Electricity Installed Capacity per Capita (Watts per Capita)	
State	Probability
<1300	0.316
(1300, 2600)	0.234
>2600	0.451

(a) Prior Probability Table

Electricity Installed Capacity (Watts per Capita)				
GDP per Capita (Constant 2005 \$U.S.)	<22818		>22818	
Natural Gas Production per Capita (Cubic Feet per Capita)	<84000	>84000	<84000	>84000
<1300	0.9	0.4	0.01	0.018
(1300, 2600)	0.025	0.457	0.01	0.182
>2600	0.075	0.143	0.98	0.8

(b) Conditional Probability Table

Figure 10. Tables for Electricity Installed Capacity per Capita**d. Electricity Installed Capacity per Capita**

The electricity installed capacity per capita node receives input from the GDP per capita and natural gas production per capita nodes, and it propagates downward into the desalination capacity per capita node. In regards to desalination capacity, high salinity water from the Arabian Gulf requires more energy capacity and, consequently, a higher cost for desalination; desalination cannot occur without an electrical infrastructure. Multi-stage flash (MSF) plants in the region demand U.S. \$0.84 per cubic meter, while multi effect distillation (MED) and seawater reverse osmosis (SWRO) plants require U.S. \$1.21 and \$1.23 respectively.⁵⁰

As documented by the U.S. Energy Information Administration, electricity capacity, converted from gigawatts to watts per capita, had 33 years of data from 1980 to 2012 for Oman, the United Arab Emirates, Saudi Arabia, and Kuwait.⁵¹ The split points for three states were 1300 watts per capita and 1600 watts per capita. These values were derived from the CIA World Factbook's country comparison for electricity installed generating capacity, where Oman ranks 79, the United Arab Emirates 34, Saudi Arabia 20, and Kuwait 50; since the countries of focus range from 20 to roughly 80, the two split points were the converted calculations of the capacity per capita for the countries a third and two-thirds down this range, Kazakhstan at 40 with a recorded 18,730,000 KW and North Korea at 60 with 9,500,000 KW.⁵²

The first table in Figure 10a shows that the data was spread fairly evenly between the bins: 31.58% for the lowest, then 23.35%, and 45.08% for the highest bin. The table in Figure 10b displays the conditional probabilities between the GDP per capita and natural gas production per capita inputs and the electricity installed capacity per capita output.

⁵⁰ The World Bank, "Renewable Energy Desalination," MENA Development Report, 2012, http://water.worldbank.org/sites/water.worldbank.org/files/publication/water-wpp-Sun-Powered-Desal-Gateway-Meeting-MENAs-Water-Needs_2.pdf (accessed November 18, 2014).

⁵¹ U.S. Energy Information Administration, "Oman."

⁵² The World Factbook, "Country Comparison: Electricity-Installed Generating Capacity," Central Intelligence Agency, 2013, <https://www.cia.gov/library/publications/the-world-factbook/rankorder/2236rank.html> (accessed March 3, 2015).

Desalination Capacity per Capita (Cubic Meters per Capita per Day)	
State	Probability
<0.3	0.323
>0.3	0.677

(a) Prior Probability Table

Desalination Capacity per Capita (Cubic Meters per Capita per Day)			
Electricity Installed Capacity per Capita (Watts per Capita)	<1300	(1300, 2600)	>2600
<0.3	0.843	0.222	0.01
>0.3	0.157	0.778	0.99

(b) Conditional Probability Table

Figure 11. Tables for Desalination Capacity per Capita**e. Desalination Capacity per Capita**

Desalination capacity per capita, as facilitated by a nation's electricity capacity, has a causal relationship with the water available per capita node. Rising from a total production of 34 million cubic meters of water per year in 1995 to 109 million cubic meters of water per year in 2006, desalination in Oman contributed to 80% of the water supply in 2010.⁵³ Oman began its program in the early 1970s with the Ghubrah plant's 7 multi-stage flash (MSF) units and another plant in Muscat. Although trailing behind Saudi Arabia as the world's largest producer, with 17% of the global desalinated water capacity, and the United Arab Emirates as the second largest producer, Oman has made strides in expanding its program; the Sohar complex today combines an MSF plant with smaller reverse osmosis (RO) and multiple-effect distillation (MED) plants to singlehandedly supply 208,000 cubic meters of water per day.⁵⁴

As extrapolated from the Economic and Social Commission for Western Asia's paper on *Strengthening Development Coordination among Regional Actors in the ESCWA Region*, Oman, the United Arab Emirates, Saudi Arabia, and Kuwait have all experienced tremendous growth in desalination since the early 1970s.⁵⁵ This dataset, however, tracked all four countries' progress over 33 years from 1980 to 2012, and it split the values into two bins at 0.3 cubic meters (or 300 liters) per capita per day; this value is double the global average daily water consumption of 150 liters, or 0.15 cubic meters, and 230 million people around the world rely solely on desalination to provide this water.⁵⁶

The table in Figure 11a indicates that most of the historical desalination capacities in the Arabian Gulf are above the 0.3 cubic meters per capita per day mark, and Figure 11b uses conditional probability to quantitatively relate electricity installed capacity per capita with desalination capacity per capita.

⁵³ Food and Agriculture Organization AquaStat, "Oman," AquaStat, 2008, http://www.fao.org/nr/water/aquastat/countries_regions/oman/index.stm (accessed November 30, 2014).

⁵⁴ Economic and Social Commission for Western Asia, "ESCWA Water Development Report 3," United Nations (2009): 12.

⁵⁵ Ibid.

⁵⁶ Veolia Water Technologies, "FAQ," Sidem, 2014, <http://www.sidem-desalination.com/en/Process/FAQ/> (accessed March 8, 2015).

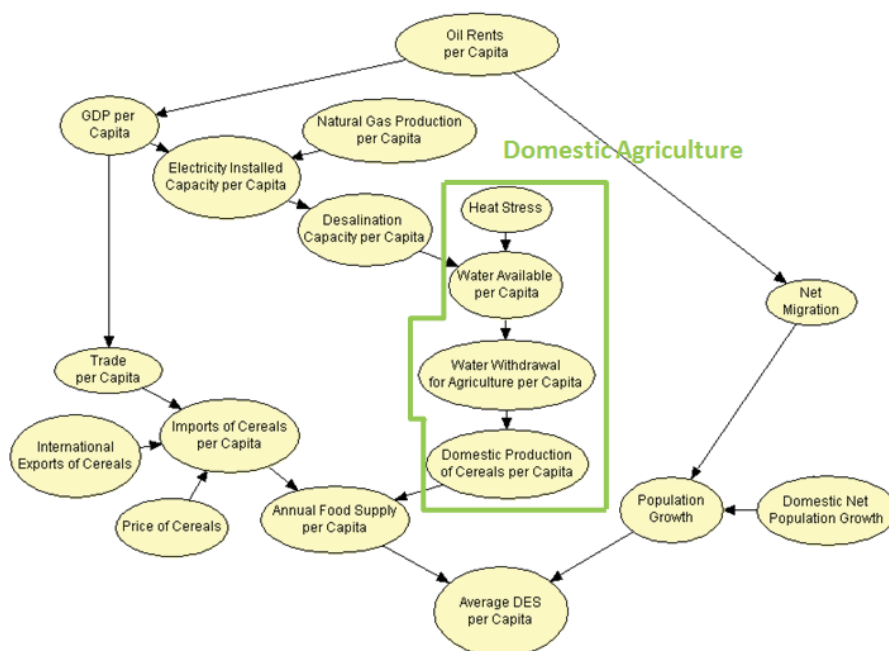


Figure 12. The Four Domestic Agriculture Variables

2. Domestic Agriculture Nodes

a. Heat Stress

When analyzing the domestic agriculture nodes in Figure 12, the heat stress node lacks a parent node, but it feeds into the water available per capita node. In the Arabian Gulf, the high temperatures and lack of rainfall make the region water insecure. If present trends with heat stress continue, two-thirds of the global population, including the Arabian Gulf, will live in water-stressed conditions by 2025.⁵⁷ Heat stress, therefore, severely affects water availability.

In generating a dataset for the heat stress variable, measured in degrees Celsius, this study referenced the National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center.⁵⁸ The dataset included only 43 points, one annually from 1970 to 2012, because heat stress is not country specific. Each year, the heat stress was calculated as the temperature difference from the 20th century average global land temperature.⁵⁹ The heat stress data was placed into two bins with a 0.5°C split point, halfway to the 1°C point at which stressed plants may begin to emit carbon dioxide, instead of absorbing through photosynthesis and respiration; land-based emissions sustained over long periods can further increase heat stress.⁶⁰

Figure 13 displays the probability distributions for the heat stress variable.

⁵⁷ World Health Organization, "Environmental Impact on Health: Children in the New Millennium," Water Sanitation Health, 2002, http://www.who.int/water_sanitation_health/hygiene/settings/millennium/en/ (accessed November 20, 2014).

⁵⁸ National Oceanic and Atmospheric Administration, "Climate at a Glance," National Climatic Data Center, 2014, <http://www.ncdc.noaa.gov/cag/time-series/global> (accessed November 18, 2014).

⁵⁹ Food and Agriculture Organization Global Agro-Ecological Zones, "GAEZ," International Institute for Applied Systems Analysis, 2014, <http://gaez.fao.org/Main.html#> (accessed November 19, 2014).

⁶⁰ Berrens, "A Degree by Degree Explanation of What Will Happen When the Earth Warms," March 20, 2015, <http://globalwarming.berrens.nl/globalwarming.htm> (accessed March 20, 2015).

Heat Stress (Degrees Celsius)	
State	Probability
<0.5	0.535
>0.5	0.465

Figure 13. Prior Probability Table for Heat Stress

Water Available per Capita (Cubic Meters per Capita per Year)	
State	Probability
<212	0.719
(212, 425)	0.077
>425	0.204

(a) Prior Probability Table

Water Available per Capita (Cubic Meters per Capita per Year)				
Desalination Capacity per Capita (Cubic Meters per Capita per Day)	<0.3		>0.3	
Heat Stress (Degrees Celsius)	<0.5	>0.5	<0.5	>0.5
<212	0.32	0.56	0.881	0.836
(212, 425)	0.26	0.04	0.01	0.073
>425	0.42	0.4	0.119	0.091

(b) Conditional Probability Table

Figure 14. Tables for Water Available per Capita

b. Water Available per Capita

The water available node has two parent nodes, and it also has one child node, water withdrawal for agriculture per capita. In terms of water consumption, 86% of Oman's water supply is used for agriculture, split evenly between industry and domestic use; the water supply subsequently affects the amount of water that can be withdrawn and consumed for agriculture.⁶¹

Water available per capita, measured in cubic meters per capita per year through the metric of total renewable resources, had data available for 43 years from 1970 to 2012 within the FAO AquaStat database.⁶² This node included the four countries of Oman, the United Arab Emirates, Saudi Arabia, and Kuwait to create 172 data points. In order to allow for a wider range of distribution, three bins were utilized with split points of 212 cubic meters per capita per year and 425 cubic meters per capita per year. These values from the World Resources Institute delineate when the nations have a year of extremely low availability (the lowest bin for this dataset) or low availability (the middle bin) of water.⁶³

⁶¹ Institute of Medicine of the National Academies, "Dietary Reference Intakes for Water, Potassium, Sodium, Chloride, and Sulfate," Food and Nutrition Board, 2005, http://www.nal.usda.gov/fnic/DRI/DRI_Water/water_full_report.pdf (accessed November 18, 2014).

⁶² Food and Agriculture Organization AquaStat, "Oman."

⁶³ Paul Reig, Andrew Maddocks, and Francis Gassert, "World's 36 Most Water-Stressed Countries," World Resources Institute, December 12, 2013, <http://www.wri.org/blog/2013/12/world%E2%80%99s-36-most-water-stressed-countries> (accessed December 1, 2014).

Water Withdrawal for Agriculture per Capita (Cubic Meters per Capita per Year)	
State	Probability
<682	0.519
>682	0.481

(a) Prior Probability Table

Water Withdrawal for Agriculture per Capita (Cubic Meters per Capita per Year)			
Water Available per Capita (Cubic Meters per Capita per Year)	<212	(212, 425)	>425
<682	0.540	0.278	0.537
>682	0.460	0.722	0.463

(b) Conditional Probability Table

Figure 15. Tables for Water Withdrawal for Agriculture per Capita

The table in Figure 14 demonstrates the heavy skew of water available towards low bins, and the bottom table shows the conditional probability relating heat stress and desalination capacity per capita to water available per capita.

c. Water Withdrawal for Agriculture per Capita

The water withdrawal for agriculture per capita node, linked above to the water available per capita node, connects to a child node of domestic production of cereals per capita. When the global population increases by about 3 billion people in the next 40 years, the food demand should also increase around 70% by 2050.⁶⁴ Since most of Oman's domestic water consumption is devoted to domestic agricultural production, water withdrawal will become devoted to rising domestic agriculture demands in Oman and elsewhere.⁶⁵

Water withdrawal for agriculture per capita, converted from billion cubic meters per year to cubic meters per capita per year, had 43 data points for each of the four countries, Oman, the United Arab Emirates, Saudi Arabia, and Kuwait. The 172 data points were found within the FAO AquaStat database, and two bins were subsequently generated.⁶⁶ The split point was 682 cubic meters per capita per year; this study estimates this value as half of the average amount of water withdrawn for agriculture in each Middle East and North Africa (MENA) country, which average a total availability of 1,429 cubic meters per capita and vary in withdrawal for agriculture.⁶⁷ Oman therefore uses nearly half as much water for agriculture than most other MENA states.

The table in Figure 15a represents the distribution of the variable's data points within its own bins, and the conditional probabilities in Figure 15b demonstrate the causal relationship between water available per capita and water withdrawal for agriculture per capita.

⁶⁴ UNESCO, "United Nations World Water Development Report 4, Managing Water under Uncertainty and Risk," World Water Assessment Programme (2012).

⁶⁵ Ibid.

⁶⁶ Food and Agriculture Organization AquaStat, "Oman."

⁶⁷ Sue Hutton, "Saving the Future – Water in Oman," Oman Economic Review, March 2003, http://www.suehutton.co.uk/articles/save_water.php (accessed November 28, 2014).

Domestic Production of Cereals per Capita (Tons per Capita per Year)	
State	Probability
<0.0045	0.601
>0.0045	0.399

(a) Prior Probability Table

Domestic Production of Cereals per Capita (Tons per Capita per Year)		
Water Withdrawal for Agriculture per Capita (Cubic Meters per Capita per Year)	<682	>682
<0.0045	0.295	0.929
>0.0045	0.705	0.071

(b) Conditional Probability Table

Figure 16. Tables for Domestic Production of Cereals per Capita**d. Domestic Production of Cereals per Capita**

Connected above with water withdrawal for agriculture per capita and below with annual food supply per capita, the domestic production of cereals per capita node demonstrates causality with Oman's food supply. Although Oman imports 80% of its food products, the nation domestically produces the remainder of its food supply.⁶⁸ Subsequently, domestic production does affect the amount of food and, therefore, calories available to Omanis.

Domestic production of cereals per capita was measured through data on the production of cereals, listed by FAOSTAT in tons and then converted to tons per capita.⁶⁹ The focus on cereals is appropriate because cereals provide the greatest number of calories to Omanis.⁷⁰ Accordingly, the data spanned from 1970 to 2012, or 43 years, for Oman, the United Arab Emirates, Saudi Arabia, and Kuwait. 0.0045 tons, or 450 kilograms, per capita acted as the split point between two bins, and the Food and Agriculture Organization notes this value as the average per capita food production in the poorest regions of the world; this 450 kilograms per capita per year is doubled to 900 kilograms per capita per year for rich countries.⁷¹

The tables in Figure 16 demonstrate the typically low domestic agriculture within Oman (with 60.01% of the data points below 0.0045 tons per capita), and the conditional probability table relates water withdrawal for agriculture per capita to domestic production of cereals per capita.

⁶⁸ Food and Agriculture Organization of the United Nations, "Food Imports by Oman Set to Grow to \$4.8bn," Regional Office for the Near East and North Africa, November 9, 2011, <http://neareast.fao.org/Pages/NewsDetails.aspx?lang=EN&id=2402627&I=0&DIId=0&CIId=0&CMSId=21> (accessed November 19, 2014).

⁶⁹ Food and Agriculture Organization Statistics Division, "Browse Data," Food Security, 2014, <http://faostat3.fao.org/browse/T/TP/E> (accessed November 20, 2014).

⁷⁰ GRM International, "Phase 1 Report."

⁷¹ Food and Agriculture Organization of the United Nations, "Cutting Food Waste to Feed the World," May 11, 2011, <http://www.fao.org/news/story/en/item/74192/icode/> (accessed March 2, 2015).

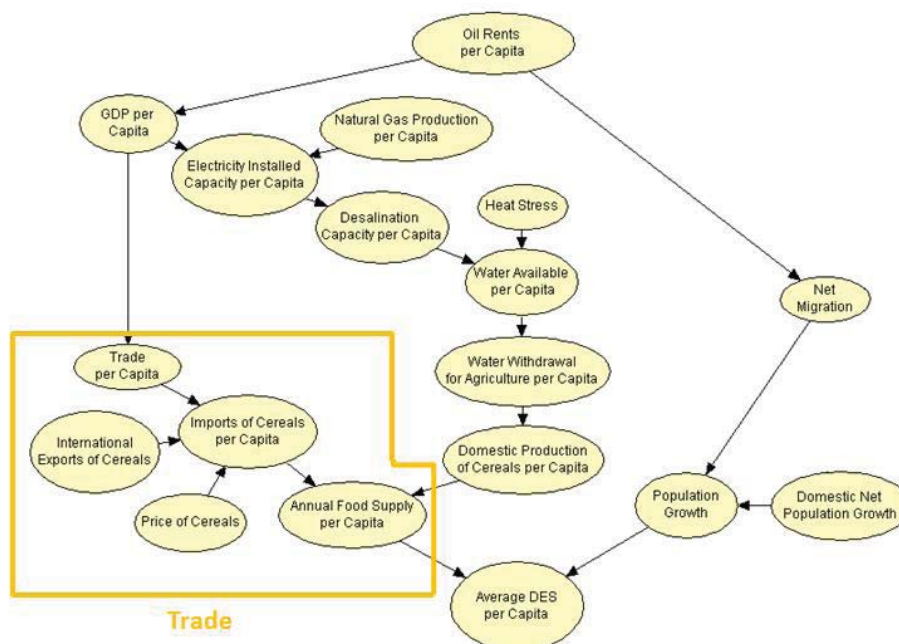


Figure 17. The Five Trade Variables

3. Trade Nodes

a. Trade per Capita

With five trade nodes in Figure 17, the trade per capita node receives input from the GDP per capita node from the energy category of nodes, and it influences the imports of cereals per capita child node. A Food and Agriculture Organization study on food security and trade found that the international dimension in food security is significant; “trade policy influences both global food availability (in the case of a major importer or exporter), and national food availability (through both imports and production).”⁷² Consequently trade, defined by the World Bank as “the sum of exports and imports of goods and services,” impacts the amount of food available for import.⁷³

With this in mind, trade per capita in this study was measured in constant 2005 U.S. dollars per capita, converted from percent of GDP by multiplying the original data by GDP per capita. Spanning from 1970 to 2012, the data, supplied by the World Bank, spanned 43 years for Oman, Saudi Arabia, and Kuwait; no data was available for the United Arab Emirates.⁷⁴ The 129 data points were divided into three bins; the lower split point was \$10,000 per capita and the higher split point is \$30,000 per capita. While not grounded in past studies, these split points appear as points of concavity on the line graphs of the data change, suggesting that the imports of food per capita starts to increase in variability around those points.⁷⁵

⁷² Food and Agriculture Organization Economic and Social Development Department, *Trade Reforms and Food Security: Conceptualizing the Linkages* (Rome, 2003), Chapter 1.

⁷³ The World Bank, “Oman: Data.”

⁷⁴ Ibid.

⁷⁵ Ibid.

Trade per Capita (Constant 2005 \$U.S. per Capita)	
State	Probability
<10000	0.281
(10000, 30000)	0.492
>30000	0.227

(a) Prior Probability Table

Trade per Capita (Constant 2005 \$U.S. per Capita)		
GDP per Capita (Constant 2005 \$U.S.)	<22818	>22818
<10000	0.505	0.01
(10000, 30000)	0.495	0.5
>30000	0.01	0.5

(b) Conditional Probability Table

Figure 18. Tables for Trade per Capita

The table in Figure 18a shows a bell-curve-like distribution, with 28.07% of the data points in the lowest bin, 49.22% in the middle, and 22.71% in the highest. The table in Figure 18b links GDP per capita to trade per capita through a conditional probability.

b. International Exports of Cereals

International exports from nations outside of the Arabian Gulf, affected by oil production in the oil-for-food trade, impact one child node, imports of cereals per capita. From the standpoint of economics, the international exports node acts like supply while the food imports per capita node acts like demand; as the 2008 cereal crisis demonstrated, an unwillingness of foreign exporters to sell food can severely limit the amount available for importation.⁷⁶

FAOSTAT provided the data for the international exports of cereals variable, measured in tons of cereal exports.⁷⁷ Cereals were chosen as the main crop because rice, flour, and wheat serve as the top three providers of energy to Omanis.⁷⁸ For this node, the data spanned 43 years from 1970 to 2012, and three foreign countries were examined: Pakistan, Thailand, and India. These countries were selected because they serve as Oman's three most significant providers of cereals, accounting for 99% of Oman's rice.⁷⁹ The two bins were split at the 5,000,000 ton mark, which this study interprets as the value that can incite a modern crisis of cereal unavailability; the 2008 crisis occurred when Pakistan and India dropped close to or below this mark.⁸⁰

Because the international exports of cereals node lacked parent nodes, the probability distribution in Figure 19 was generated by merely dividing the number of cases per bin by the number of data points.

⁷⁶ Anuradha Mittal, "The 2008 Food Price Crisis: Rethinking Food Security Policies," *G-24 Discussion Paper Series* no. 56 (2009). http://unctad.org/en/docs/gdsmdpg2420093_en.pdf (accessed December 10, 2013).

⁷⁷ Food and Agriculture Organization Statistics Division, "Browse Data."

⁷⁸ GRM International, "Phase 1 Report."

⁷⁹ Ibid.

⁸⁰ Food and Agriculture Organization Statistics Division, "Browse Data."

International Exports of Cereals (Tons)	
State	Probability
<5,000,000	0.636
>5,000,000	0.364

Figure 19. Prior Probability Table for International Exports of Cereals

Price of Cereals (Constant 2005 \$U.S. per Metric Ton)	
State	Probability
<140	0.698
>140	0.302

Figure 20. Prior Probability Table for Price of Cereals

c. Price of Cereals

The price of cereals node does not have any parent nodes, but it propagates downward into the import of cereals per capita node. Price connects to demand, represented by cereal imports in this model, in macroeconomics because a high price drives down demand, whereas a low price encourages buying and increases demand.⁸¹ In 2008, the food price spike contributed directly to the collapse of demand and, subsequently, the global market.⁸²

In this model, price was measured for cereals, the main energy supplier in Omanis' diets, in constant 2005 U.S. dollars per metric ton. The data spanned 43 years from 1970 to 2012, but the data was not country specific and, therefore, required only 43 data points. The United States Department of Agriculture Economic Research Service presented the data at a monthly interval, so the average of the twelve months' prices represented the year as a whole.⁸³ \$140 per metric ton served as the split point for the two bins, appearing as a recurring point of concavity on the line graph of the data; this concavity suggests that the prices change at a faster rate around \$140 per metric ton and therefore produce greater variability in cereal imports.⁸⁴

Without a parent node, the probability distributions in Figure 20 simply represented the number of cases per bin for price divided by 43, the number of data points.

d. Imports of Cereals per Capita

The food imports per capita node receives data from three parent nodes, trade per capita, international exports of cereals, and prices of cereals, and it connects to the annual food supply per capita node beneath it. In contributing to the total amount of food available for consumption by the population, food imports account for 90% of the Gulf Cooperation Council's food supply and 80% of Oman's food supply. Furthermore, these imports are expected to grow to \$4.8 billion

⁸¹ Library of Economics and Liberty, "Supply and Demand, Markets and Prices," Econlib Resources, 2012, <http://www.econlib.org/library/Topics/College/supplyanddemand.html> (accessed November 20, 2014).

⁸² Anuradha Mittal, "The 2008 Food Price Crisis: Rethinking Food Security Policies."

⁸³ United States Department of Agriculture, "Wheat Data," Economic Research Service, November 20, 2014, <http://www.ers.usda.gov/data-products/wheat-data.aspx#25278> (accessed November 20, 2014).

⁸⁴ Ibid.

Imports of Cereals per Capita (Tons per Capita)	
State	Probability
<0.25	0.602
>0.25	0.398

(a) Prior Probability Table

Imports of Cereals per Capita (Tons per Capita)												
Price of Cereals (Constant 2005 \$U.S./Metric Ton)	<140						>140					
International Exports of Cereals (Tons)	<5			>5			<5			>5		
Trade per Capita (Constant 2005 \$U.S./Capita)	<10000	(,)	>30000	<10000	(,)	>30000	<10000	(,)	>30000	<10000	(,)	>30000
<0.25	0.814	0.763	0.926	0.294	0.159	0.333	0.812	0.8	0.99	0.25	0.143	0.1
>0.25	0.186	0.737	0.074	0.706	0.841	0.667	0.188	0.2	0.01	0.75	0.857	0.9

(b) Conditional Probability Table

Figure 21. Tables for Imports of Cereals per Capita

and over 3.2 million tons, a 5.3% increase from 2011, by 2020.⁸⁵

FAOSTAT contributed 43 years of data from 1970 to 2012 on the import of cereals, converted from tons to tons per capita by dividing by population.⁸⁶ 172 data points were aggregated from four countries, Oman, the United Arab Emirates, Saudi Arabia, and Kuwait, and cereals were the focus in order to stay consistent with the rest of the nodes in the trade category. The split point for the two bins was 0.25 tons per capita, the value that this study anticipates would result in insufficient cereal imports, as in 2004 when China's cereal stocks hit their lowest point since the early 1980s and when the United States and European Union began their two-year decline in wheat and maize production.⁸⁷

The table in Figure 21a demonstrates a skew towards imports of cereals under 0.25 tons per capita, enabling better observation of the recent rise in imports. The table in Figure 21b shows the conditional probabilities between trade per capita, international exports of cereals, price of cereals, and imports of cereals per capita.

e. Annual Food Supply per Capita

The annual food supply per capita node has two parent nodes, imports of cereals per capita and domestic production of cereals per capita, and one child node, the network's final node. Since average Daily Energy Supply (DES) is measured as kilocalories per person per day, its two parent nodes divide according to that unit of measurement. Consequently, the population growth node contributes to the "person" measurement while the annual food supply node covers the "kilocalories," shifting from the weight of food available to the caloric intake available to people; not all of the food supply reaches human consumption because, for instance, livestock and camels consume fodders and cereal feed.⁸⁸ Additionally, the government diverts cereals to

⁸⁵ Food and Agriculture Organization of the United Nations, "Food Imports by Oman Set to Grow to \$4.8bn."

⁸⁶ Food and Agriculture Organization Statistics Division. "Browse Data."

⁸⁷ Joachim von Braun, "The World Food Situation: New Driving Forces and Required Actions," International Food Policy Research Institute, December 2007, <http://www.ifpri.org/sites/default/files/publications/pr18.pdf> (accessed March 1, 2015).

⁸⁸ Mohammed Al-Mashakhi and El-Hag Koll, "Oman: Country Pasture/Forage Resource Profiles," Food and Agriculture Organization of the United Nations, April 2007, <http://www.fao.org/ag/agp/AGPC/doc/Counprof/oman/oman.htm> (accessed March 2, 2015).

Annual Food Supply per Capita (Kilograms per Capita per Year)	
State	Probability
<150	0.663
>150	0.337

(a) Prior Probability Table

Annual Food Supply per Capita (Kilograms per Capita per Year)				
Imports of Cereals per Capita (Tons per Capita)	<0.25		>0.25	
Domestic Production of Cereals per Capita (Tons per Capita per Year)	<0.0045	>0.0045	<0.0045	>0.0045
<150	0.864	0.611	0.5	0.531
>150	0.136	0.389	0.5	0.469

(b) Conditional Probability Table

Figure 22. Tables for Annual Food Supply per Capita

strategic storage sites, creating the most developed storage system in the GCC; in 2010, Oman stored the equivalent of one year of rice, six months of edible sugar, oils, and milk, and five months of wheat, and Oman has plans to amplify wheat storage up to 17 months at the ports of Sohar and Salalah.⁸⁹

Annual food supply per capita is measured in kilograms per capita per year. The data was available through FAOSTAT for 43 years for Oman, the United Arab Emirates, Saudi Arabia, and the UAE, combining into 172 data points.⁹⁰ The split point used for the two bins was 150 kilograms per capita per year. This value is equivalent to the amount of wheat needed for a low-level consumption diet, where the wheat provides a daily caloric value of about 1,200 and supplementary foods provide additional caloric intake.⁹¹

As the table in Figure 22a demonstrates, the data favors the lower bin of less than 150 kilograms per capita per year. The table in Figure 22b shows the conditional probabilities between imports of cereals per capita, domestic production of cereals per capita, and annual food supply per capita.

4. Human Factor Nodes

a. Net Migration and Domestic Net Population Growth

In regards to the four human factors variables in Figure 23, net migration and domestic net population growth represent the various ways a person can enter or leave a nation or contribute to the population within the country. Subsequently, they contribute to the rate of change in their population growth child node.

Net migration data, measured in the unit of people per year, was compiled from the World Bank. Domestic net population growth, calculated by subtracting the death rate from the

⁸⁹ Eckart Woertz, *Oil for Food: The Global Food Crisis and the Middle East* (Oxford: Oxford University Press, 2015), 214.

⁹⁰ Food and Agriculture Organization Statistics Division, "Browse Data."

⁹¹ Nicholas Lardy, *Agriculture in China's Modern Economic Development* (Cambridge: Cambridge University Press, 1983), 170.

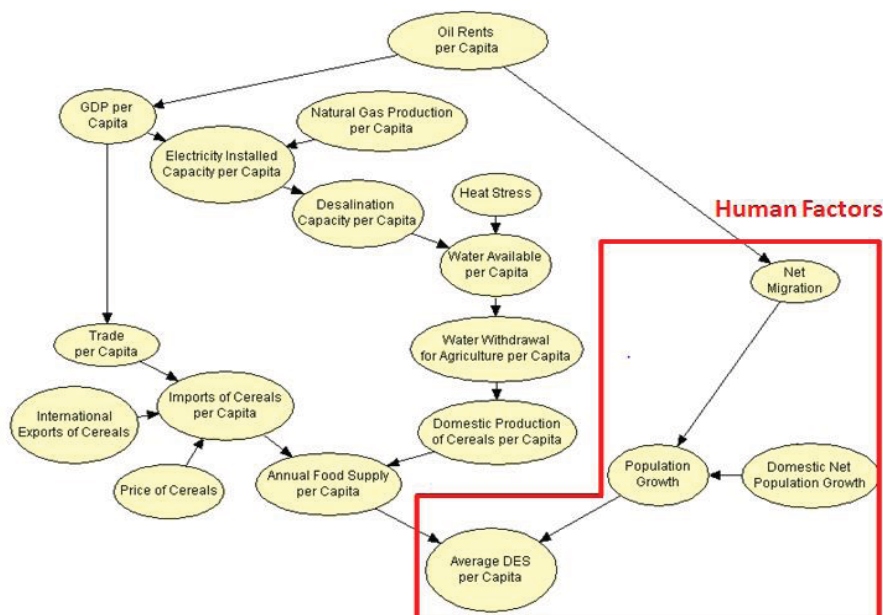


Figure 23. The Four Human Factor Variables

birth rate and measured per 1,000 people, came from the same World Bank source.⁹² 43 data points were recorded for each variable for each of the four countries: Oman, the United Arab Emirates, Saudi Arabia, and Kuwait. In regards to the 172 total points for each variable, net migration was divided into three bins split at 20,000 and 100,000 people per year; 100,000 people per year serves as the lowest value for annual net migration for the top ten Muslim countries (where Oman and the United Arab Emirates currently fall), and 20,000 is the lower bound for the top fifteen (where Saudi Arabia and Kuwait currently reside).⁹³ The domestic net population growth had two bins, split at 20 per 1,000 people, considered a high rate; one-sixth of the world's population experiences this high rate, predominantly in countries in Africa, Latin America, and Western and Southern Asia.⁹⁴

The table in Figure 24a shows the bell-curve-like shape of the net migration data within its bins, and Figure 24b is the conditional probability distribution between oil rents per capita and net migration. Figure 24c indicates a left-skewed probability distribution for the parentless domestic net population growth variable.

⁹² The World Bank, "Oman: Data."

⁹³ NationMaster, "Net Migration: Countries Compared," 2005, <http://www.nationmaster.com/country-info/stats/People/Migration/Net-migration> (accessed March 12, 2015)

⁹⁴ Harold Damerow, "Population Geography," Union County College, January 2015, http://faculty.ucc.edu/egh-damerow/population_geography.htm (accessed March 2, 2015).

Net Migration (per Year)	
State	Probability
<20000	0.282
(20000, 100000)	0.486
>1000000	0.232

(a) Prior Probability Table for Net Migration

Net Migration (per Year)			
Oil Rents per Capita (Constant 2005 \$U.S. per Capita)	<5000	(5000, 10000)	>10000
<20000	0.667	0.175	0.01
(20000, 100000)	0.123	0.456	0.879
>100000	0.211	0.368	0.121

(b) Conditional Probability Table for Net Migration

Domestic Net Population Growth (per 1,000 people)	
State	Probability
<20	0.343
>20	0.657

(c) Prior Probability Table for Domestic Net Population Growth

Figure 24. Tables for Net Migration and Domestic Net Population Growth**b. Population Growth**

The population growth node has two parent nodes and the network's final node as its child node. Since average Daily Energy Supply (DES) is measured as kilocalories per person per day, its two parent nodes divide according to that unit of measurement. As mentioned before, the population growth node provides the "person" measurement while the annual food supply per capita node covers the "kilocalories" in the form of food supply.

Population growth was based off data from the World Bank. Available for 43 years for Oman, the United Arab Emirates, Saudi Arabia, and Kuwait, the data combined into 172 points, measured as percentiles.⁹⁵ The one split point used for the two bins was 4%, representing high population growth during two different phenomena: 1) the decrease in death rates after the 1960s in the developing world, which preceded the decline of birth rates and 2) modern economic growth and human development in developing countries.⁹⁶

As the table in Figure 25a demonstrates, the Arabian Gulf population has grown significantly in recent years, and the table in Figure 25b shows the conditional probabilities between net migration, domestic net population growth, and total population growth.

⁹⁵ The World Bank, "Oman: Data"

⁹⁶ Tatyana Soubbotina, "Beyond Economic Growth: An Introduction to Sustainable Development," The World Bank Institute, September 2004, http://www.worldbank.org/depweb/beyond/beyondco/beg_03.pdf (accessed November 28, 2014)

Population Growth (Percentile)	
State	Probability
<4	0.385
>4	0.615

(a) Prior Probability Table

Population Growth (Percentile)						
Net Migration (per year)	<20000		20000, 100000		>100000	
Domestic Net Population Growth (per 1,000 people)	<20	>20	<20	>20	<20	>20
<4	0	0.590	0.6	0.093	0.25	0.2
>4	0.01	0.410	0.4	0.907	0.75	0.8

(b) Conditional Probability Table

Figure 25. Tables for Population Growth**c. Average Daily Energy Supply (DES)**

Meeting daily standards for energy supply will enable both expatriates and nationals in Oman to live active lifestyles. Accordingly, average daily energy supply (DES) serves as the final node in the network.

The dataset for average DES came from the Food and Agriculture Organization of the United Nations Statistics Division (FAOSTAT). Unfortunately there was no data specifically for Oman for this variable, measured in kilocalories per person per day, so the 129 included data points spanned from the years 1971 to 2012 for the three Arabian Gulf countries listed in the FAOSTAT database: the United Arab Emirates, Saudi Arabia, and Kuwait.⁹⁷ Due to data constraints, this project operates with the assumption that other nations' data can serve as an estimated values for Oman. In fact, the GRM International Report indicates a close correlation between Oman and Kuwait.⁹⁸ The node utilized four different bins, and the lowest split point was the comfortable lower bound for DES established in the GRM International Report, 2,100 kilocalories per person per day. The second split point was 3,000 kilocalories per person per day, which is a high boundary for caloric intake for children, the recommended intake for women with heavy work, and the recommended value for moderately active men.⁹⁹ The third split point was 3250 kilocalories per person per day, the average food intake in the world's developed countries.¹⁰⁰ And the highest split point, 3,500 kilocalories per person per day, obesity becomes more of a threat because 3,500 kilocalories comprise one pound of fat.¹⁰¹ With these split points, the data adopted a bell-shaped structure for the purpose of sensitivity testing.

Figure 26a shows the skew toward high DES, and Figure 26b shows the conditional probabilities relating annual food supply per capita, population growth, and average DES.

⁹⁷ Food and Agriculture Organization Statistics Division, "Browse Data."

⁹⁸ GRM International, "Phase 1 Report."

⁹⁹ Nirali Prakashan, *A Text Book of Nutrition for Nurses* (Mumbai: Pragati Books, 2008), 4.

¹⁰⁰ Joel Cohen, *How Many People Can the Earth Support?* (New York: W.W. Norton, 1995), 219.

¹⁰¹ Centers for Disease Control and Prevention, "Losing Weight," August 17, 2011, http://www.cdc.gov/HEALTHYWEIGHT/LOSING_WEIGHT/INDEX.HTML (accessed November 27, 2014).

Average DES (Kilocalories per Person per Day)	
State	Probability
<2100	0.048
(2100, 3000)	0.277
(3000, 3250)	0.310
(2350, 3500)	0.303
>3500	0.062

(a) Prior Probability Table

Average DES (Kilocalories per Person per Day)				
Annual Food Supply per Capita (Kilograms per Capita per Year)	<150		>150	
Population Growth (Percentile)	<4	>4	<4	>4
<2100	0.038	0.086	0.01	0.01
(2100, 3000)	0.346	0.333	0.289	0.075
(3000, 3250)	0.232	0.285	0.344	0.444
(3250, 3500)	0.346	0.259	0.315	0.333
>3500	0.038	0.037	0.052	0.148

(b) Conditional Probability Table

Figure 26. Tables for Average Daily Energy Supply (DES)

With five Energy nodes, four Domestic Agriculture, five Trade, and four Human Factor variables, the Bayesian belief network consists of eighteen nodes that outline the basic structure of Oman's food security environment. The organization of the variables is important in measuring the sensitivity of average DES to different potential crises. Before this testing can begin, though, weak points in the model must be explored.

IV. Comparing the Model to Reality

To evaluate the model against reality, this study compared the probability distribution of average DES to the actual value of DES in Oman for each year in the Bayesian belief network. First, though, a unique model had to be constructed for each year, including data for every year except the one being tested; the exclusion of the test year ensured that the model would not already have adjusted for anomalies in that year. The models retained the same structure for the eighteen variables, but the probability distributions for the nodes were slightly different in each of the 43 years' models.

To emulate reality in each year, the parentless nodes in the network were fixed to the outcomes that had the actual value for the excluded year. The Bayesian belief network in this study had six variables without parent nodes—(1) oil rents per capita, (2) natural gas production per capita, (3) heat stress, (4) international exports of cereals, (5) price of cereals, and (6) domestic net population growth. Each of these variables had two states, except for oil rents per capita with three. In each of the 43 years, fixing these bins to reflect the excluded values caused the probability distribution of average DES to change.

Year	Successful	Bad
1970	X	
1971	X	
1972	X	
1973	X	
1974		X
1975		X
1976		X
1977		X
1978		X
1979	X	
1980	X	
1981	X	
1982	X	
1983	X	
1984		X
1985	X	
1986	X	
1987		X
1988	X	
1989	X	
1990		X
1991		X
1992		X
1993		X
1994	X	
1995	X	
1996	X	
1997	X	
1998	X	
1999	X	
2000		X
2001	X	
2002	X	
2003	X	
2004	X	
2005	X	
2006	X	
2007	X	
2008	X	
2009	X	
2010	X	
2011	X	
2012	X	
Total	31	12

Figure 27. Successful and Bad Years for the Model

To determine the “success” of the model in a given year, the state of average DES that contained the actual, excluded DES value needed to increase in likelihood within the probability distribution; the Bayesian belief network should predict a higher chance of that value occurring. Contrarily, if the outcome with the excluded value decreased in probability, the model was deemed “bad.”

For example, in 1970 oil rents per capita was fixed to its lowest bin of less than constant 2005 \$5000 per capita due to an actual value of \$3074.39 per capita; natural gas production per capita to its lower bin of less than 84000 cubic feet per capita due to an actual value of 24255.55 cubic feet per capita; heat stress to its lower bin of less than 0.5° C due to an actual value of 0.02° C; international exports of cereals to its lower bin of less than 5,000,000 tons due to an actual value of 972,069 tons; price of cereals to its lower bin of less than constant 2005 \$140 due to an actual value of \$50.40; and domestic net population growth to its higher bin of greater than 20 people per 1000 due to an actual value of 32 per 1000. In this year, the actual value of average DES was 2930 kilocalories/person/day, which fell within the second lowest state with a range of 2100 to 3000 kilocalories/person/day. When the parent nodes were fixed to reflect their actual values, the probability of the second lowest state increased from an original value of 27.66% to 29.04%. Accordingly, the model was deemed “successful” for 1970.

Using this method, 31 of the 43 years, or 74%, had “successful” results, as shown in Figure 27; the appropriate state for average DES increased in probability after the parent nodes were fixed. For the remaining 12 “bad” years, similar combinations of states in the parent nodes produced the negative results. In the 43 years, 12 different combinations of the parent nodes’ states occurred, and the “bad” nodes resulted within 5 of those combinations.

The combination that produced the most “bad” results, 6 of the 12, fixed oil rents per capita to its lowest bin (<constant 2005 \$5000 per capita), natural gas production to its lower bin (<84000 cubic feet per capita), heat stress to its lower bin (<0.5° C), international exports of cereals to its lower bin (<5,000,000 tons), price of cereals to its lower bin (<constant 2005 \$140), and domestic net population growth to its higher bin (>20 people per 1000). In the four years from 1975 and 1978, this combination unsuccessfully predicted the middle state of average DES, where the actual values fell between 3000 and 3250 kilocalories/person/day. For these cases,

the unexpected behavior is attributed to oil rents per capita values close to the constant 2005 \$5000 per capita split point; these years would have been better represented by the combination for 1979, with all the same states for the parent nodes except the higher bin for oil rents per capita, that saw an increase in probability in average DES’ middle bin. The average DES in the years 1975 to 1978 may have been higher than the model predicted because of the growing surplus in the Arabian Gulf countries’ balance of payments deficits due to oil, as opposed to the

growing deficits in Western nations of the Organization for Economic Cooperation and Development (OECD).¹⁰² In 1984 and 1987, the “bad” combination also mistakenly saw a decrease in probability for the highest state of average DES, having actual values above 3500 kilocalories/person/day; these problem years were also associated with values close to the split point for oil rents per capita, perhaps explained by the fact that at the end of both of these years the Organization of the Petroleum Exporting Countries and other Arabian Gulf nations attempted to cut oil production.¹⁰³ Accordingly, actual values near the split point for the oil rents per capita node can help explain half of the “bad” results.

Between 1990 and 1993, 4 additional “bad” results occurred, stemming from 2 different combinations that differed only in the states for heat stress, which barely caused any change in the probability distribution for average DES; 1990 and 1991 had heat stress above 0.5° C while 1992 and 1993 had the opposite. Both combinations, however, had the lowest bin for oil rents per capita, the higher for natural gas production, the lower for international exports, the lower for prices, and the higher for domestic population growth. In these four cases, the Persian Gulf War, where Saddam Hussein of Iraq ordered the invasion of Kuwait, drove up the revenue requirements of oil-producing Arabian Gulf nations.¹⁰⁴ Consequently, this unanticipated change in economic stability pushed the probability distribution of average DES towards food insecurity; the lowest and second lowest states increased in probability distribution, while the middle outcome that had the actual values for average DES decreased in likelihood.

The last two “bad” results and combinations occurred in 1974 and 2000. In 1974, the parent nodes’ actual values were identical to those between 1975 and 1978, except for an actual value of constant 2005 \$153.72 for prices and the use of the higher state for that variable. The actual value for average DES fell within the middle state, and the decrease in the probability for that outcome may again be caused by a value near the oil rents per capita split point. In 2000, oil rents per capita had its middle state, natural gas production per capita its higher, heat stress its higher, international exports its lower, prices its lower, and domestic population growth its higher outcome, and it unsuccessfully predicted the second highest outcome for average DES, falling between 3250 and 3500 kilocalories/person/day. This year is the only “bad” year disassociated from oil behavior.

Overall, the Bayesian belief network produced changes in probability distribution that mostly corresponded with the actual yearly average DES values. As demonstrated now and will be shown again in the next section, however, the different states of oil rents per capita in the Energy cluster of variables can produce confounding probability distributions.

V. Crisis Testing

After comparing the Bayesian belief network to actual values for average DES, the project then measured the sensitivity of average DES in possible crises. This testing involved fixing the values of certain nodes and calculating the change in probability distribution for the

¹⁰² Siamack Shojai, *The Oil Market in the 1980's: A Decade of Decline* (New York: Greenwood Publishing Group, 1992), 32.

¹⁰³ Benoit Faucon, Summer Said, and Andrew Peale, “Falling Oil Prices Test OPEC Unity,” *The Wall Street Journal*, November 16, 2014, <http://www.wsj.com/articles/falling-oil-prices-test-opec-unity-1416188605> (accessed March 14, 2015).

¹⁰⁴ Eliyahu Kanovsky, “The Economic Consequences of the Persian Gulf War: Accelerating OPEC’s Demise,” *The Washington Institute*, 1992, http://www.washingtoninstitute.org/uploads/Documents/pubs/PP_30_AcceleratingOPECsDemise.pdf (accessed March 15, 2015), 99.

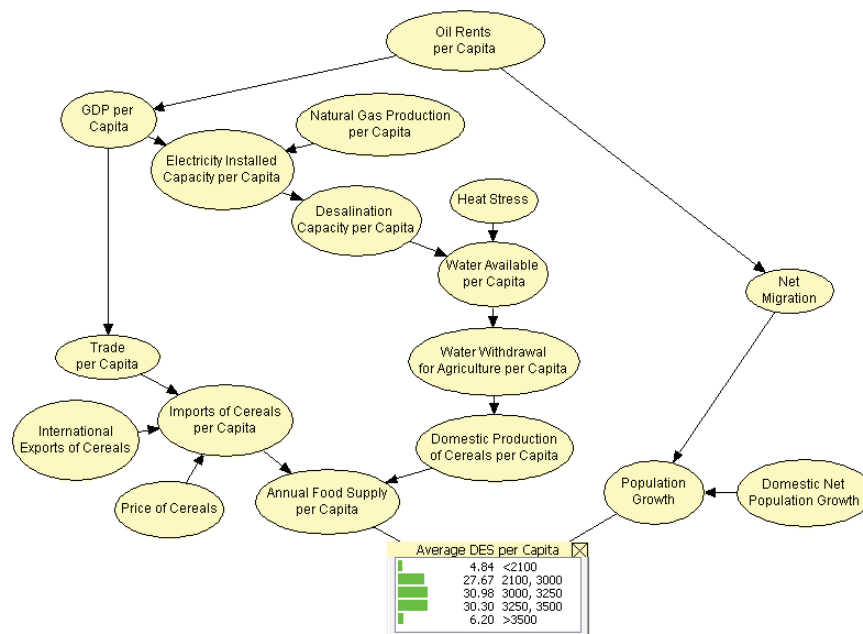


Figure 28. Original Probability Distribution for Average Daily Energy Supply (DES)

final node, average DES. The change for each state in the probability distribution was derived by subtracting the final probabilities from the originals, displayed in Figure 28. Note that average DES had an initial distribution of 4.84% for its lowest bin, 27.67% for the next, 30.98% in the middle, 30.30% in the second highest, and 6.20% in the highest bin.

1. International Refusal to Sell Cereals

The first crisis for observation attempted to emulate the 2008 global food price spike. That year, the price of cereals nearly tripled from \$386 per ton in 2008. International exporters reduced availability from 4,309,986 tons in 2007 to 3,204,774 tons in 2008. The effects of these changes propagated into Oman's ability to import cereals, subsequently obtaining only 646,160 tons of cereals in 2008.¹⁰⁵ Accordingly, the scenario involving the international refusal to sell cereals fixed the probability distributions of two nodes: international exports of cereals was fixed to its lower state of less than 5,000,000 tons, and the price of cereals node was set to its higher outcome of greater than \$140 per metric ton. While this split point does not fully characterize the severity of the price shock, the fixing of this bin to the higher state still helps demonstrate the effects on average DES. Figure 29a displays the subsequent changes in the Bayesian belief network, and Figure 29b calculated the changes in probability distribution for each state in average DES. In this scenario, the likelihood of Oman having a lower average DES increased, as the lowest state and second lowest state respectively increased 0.36% and 1.13% in probability. All bins in excess of 3,000 kilocalories per person per day decreased in probability. The middle bin dropped 0.84%, the second highest by 0.19%, and the highest by 0.44%. Although these probability changes seem statistically small, this project interprets changes above 0.10% as important to sensitivity. The main focus, though, is the direction of the changes.

¹⁰⁵ The World Bank, "Oman: Data."

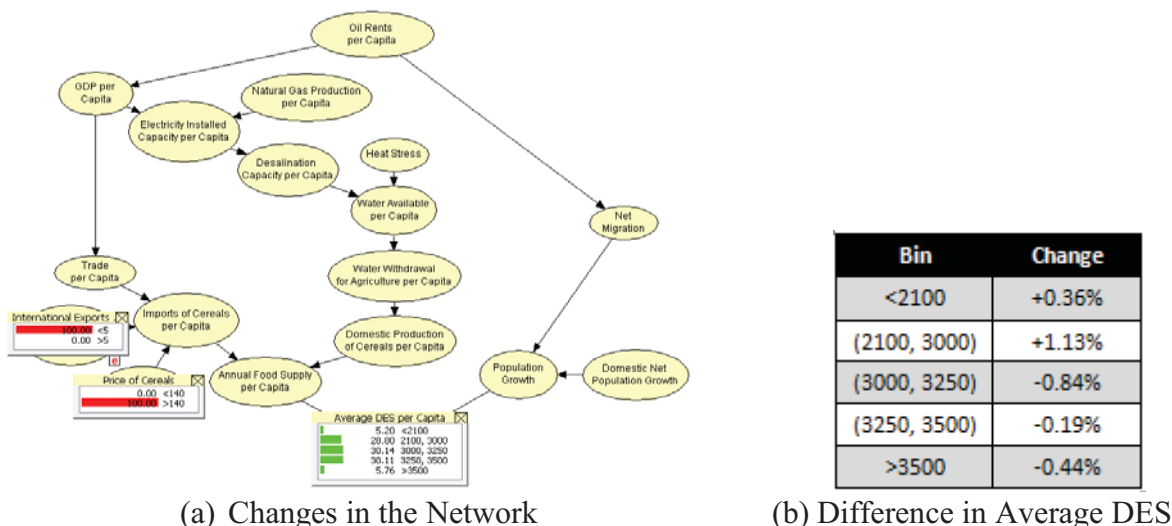


Figure 29. Change in Probability Distribution During an International Refusal to Sell Cereals

2. Plummet in the Price of Oil

A second crisis scenario focuses on the importance of oil in the global exchange of food. As oil rents per capita act as the first node in the Bayesian belief network, a dramatic shift in the price of oil affects the entire network, all the way down to average DES. Since June 2014, oil prices have more than halved from \$110 a barrel to below \$50 a barrel, sitting at their lowest level since May 2009.¹⁰⁶ These low prices strain Arabian Gulf economies, as Kuwait needs a long-term price of \$79 per barrel to balance its budget, the UAE \$81, and Saudi Arabia \$104.¹⁰⁷ To emulate these effects in Figure 30a, oil rents per capita was fixed to its lowest bin of less than \$5000 per capita. In this scenario, the change in probability distribution for average DES produced less conclusive results in Figure 30b, as the lowest bin decreased 0.58% while the second lowest increased 1.38% in probability. The middle bin and highest bin also decreased while the second highest bin increased in probability. Unaccounted for external factors may produce the inconclusiveness of the results, or alternatively, a decrease in oil rents may have short-term positive and negative effects on food security; while higher oil prices and oil rents, for instance, bolster the buying power of Arabian Gulf nations and increase the annual food supply, the economic boom may attract more expatriates and create unsustainable population growth.

¹⁰⁶ Tim Bowler, "Failing Oil Prices: Who are the Winners and Losers?," BBC News, January 19, 2015, <http://www.bbc.com/news/business-29643612> (accessed February 28, 2015).

¹⁰⁷ Ibid

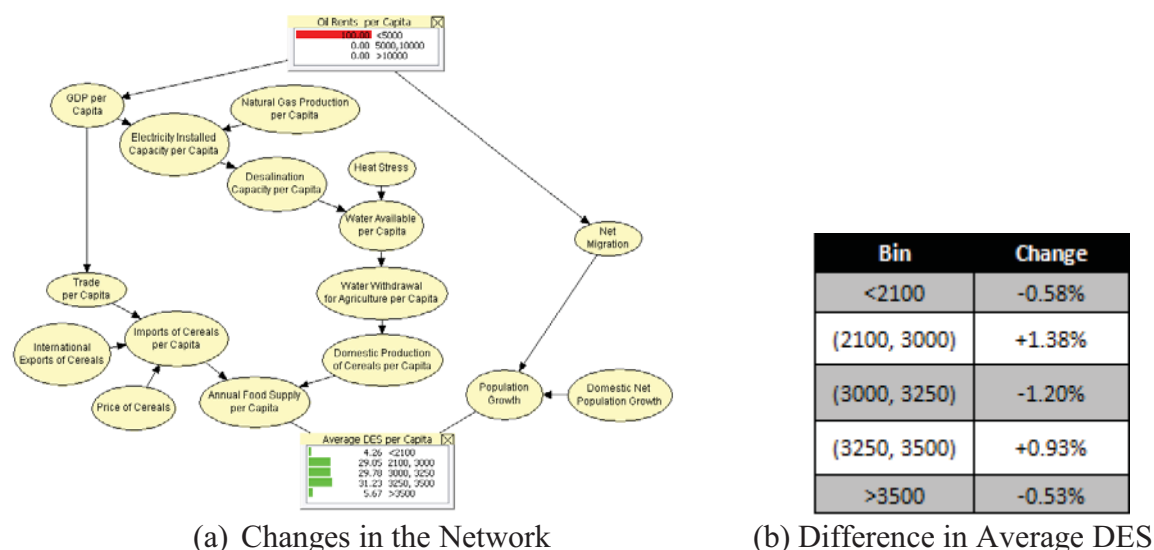


Figure 30. Change in Probability Distribution During a Plummet in the Price of Oil

3. Mass Emigration of the Expatriate Workforce

In February 2014, the expatriate population in Oman reached 1.7659 million to comprise 44.2% of the nation's entire population. Of the 1.7659 million, 1.5345 million provide crucial work in the Omani economy, but especially construction and infrastructure projects. Therefore, if, for instance, the Omani government dramatically cuts its 3.2 billion Omani riyal allocation, 24% of overall public expenditure, for investment expenditure, the lack of work could encourage a mass emigration of the expatriate workforce from Oman.¹⁰⁸ The effects of this population shift could cripple the economy and food security situation. To simulate this scenario in Figure 31a, net migration was fixed to its lowest bin of less than 20,000 people, wherein the value for a given year could be negative. The resulting change in probability distribution for average DES produced a minor effect in Figure 31b, but there was a greater shift towards the lower, food-insecure bins. Although the lowest bin decreased 1.10%, the second lowest bin increased more than the second highest bin in probability, respectively 2.72% and 1.77%. The middle bin and highest bin both decreased at 2.34% and 1.04%. One possible explanation for the results is the duality of the short-term effects of mass emigration. With fewer people in Oman, the remaining people would have a greater caloric share per person, but the economic vitality Oman needs to obtain the food would become diminished.

¹⁰⁸ A.E. James, "Oman Expatriate Population Touches 1.766 Million," Times of Oman, April 6, 2014, <http://bluecodedesoft.timesofoman.com/news/32073/Article-Oman-expatriate-population-touches-1%20766-million> (accessed November 5, 2014).

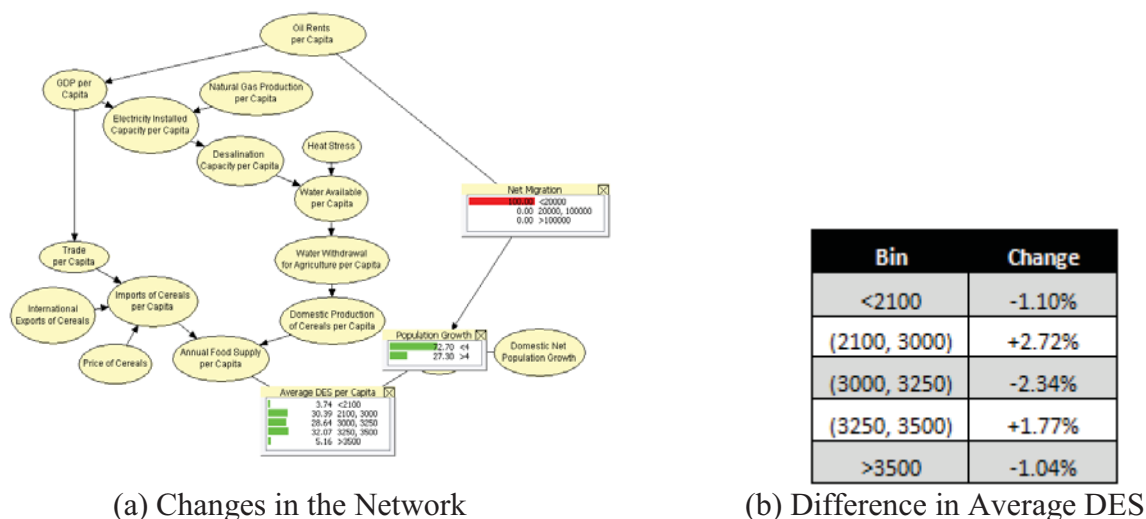


Figure 31. Change in Probability Distribution During a Mass Emigration in the Expatriate Workforce

4. Drought

Drought is one of the most damaging natural disasters, causing millions of deaths and hundreds of billions of dollars worldwide since 1967.¹⁰⁹ In the Arabian Peninsula, increasing global temperatures, decreasing soil moisture, and rising evapotranspiration through planned agriculture threaten the already arid land, which indirectly affects the domestic production of cereals per capita.¹¹⁰ This scenario measures the effects of a decrease in water available for any reason, fixing the lowest bin in Figure 32a of less than 212 cubic meters per capita in the water available per capita node. With negative 0.10% as the largest change of probability for a bin in average DES in Figure 32b, the small changes in the probability distribution indicate that drought may have less severe effects than the other crises. Accordingly to the threshold of 0.10% for importance to sensitivity, none of the states of average DES experience a substantive change. This conclusion is cogent because Arabian Gulf nations have taken measures since 2000 to manage water resources, combat desertification, and reuse wastewater.¹¹¹ It is worth noting, though, that future climate predictions based on IPCC AR5 climate forecasts through 2100 suggest more frequent droughts and climate extremes, especially for Middle Eastern locations.¹¹²

¹⁰⁹ Rajiv Sinha and Rasik Ravindra, "Earth System Processes and Disaster Management," Springer Science & Business Media, August 13, 2012, 172.

¹¹⁰ Ibid.

¹¹¹ Othman Al-Alawi, "Drought Conditions and Management Strategies in Sultanate of Oman," Ministry of Agriculture and Fisheries, 2014, http://www.ais.unwater.org/ais/pluginfile.php/605/mod_page/content/22/Oman.pdf (accessed March 3, 2015).

¹¹² Intergovernmental Panel on Climate Change Working Group I, "Fifth Assessment Report of the Intergovernmental Panel on Climate Change."

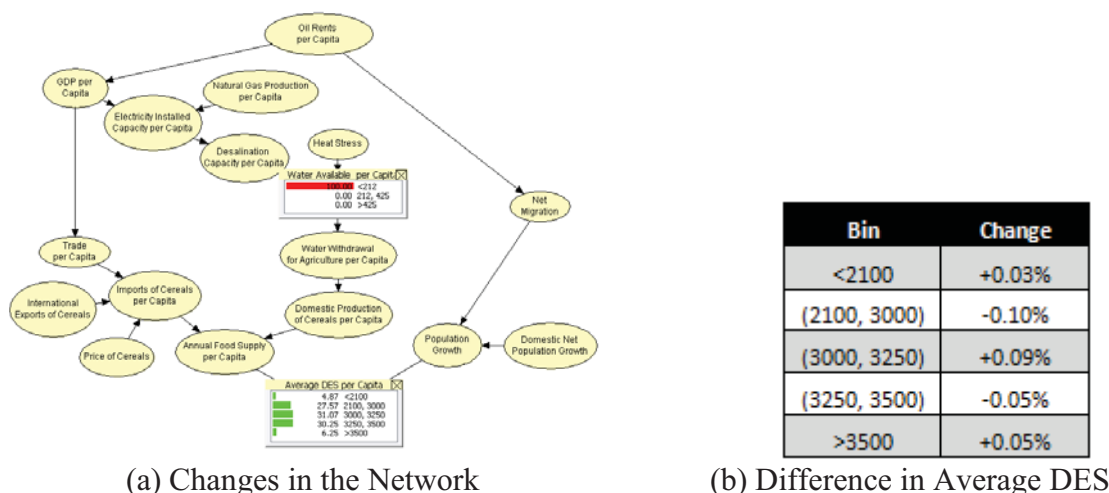


Figure 32. Change in Probability Distribution During a Drought

5. Attack on Strategic Storage Sites

As previously discussed, Oman's Public Authority for Stores and Food Reserve has established warehouses to stockpile minimum thresholds of food commodities. Another potential crisis would be the destruction of strategic warehouses through enemy attack, natural disaster, or another means of compromising the stored food.¹¹³ To simulate this scenario in Figure 33a, or any other massive loss in food supply through transportation and storage issues, the annual food supply per capita node was fixed to its lower bin of 150 kilograms per capita per year, indicating that food availability may drop below this mark. Figure 33b calculated the changes in probability distribution for each bin in average DES, greatly increasing the likelihood of Oman having a lower average DES and becoming more food insecure. The lowest bin and second lowest bin respectively increased 1.96% and 6.16% in probability. The bins with split points greater than 3,000 kilocalories per person per day each decreased in probability. The middle bin dropped 4.45%, the second highest by 1.03%, and the highest by 2.44%.

¹¹³ Woertz 214.

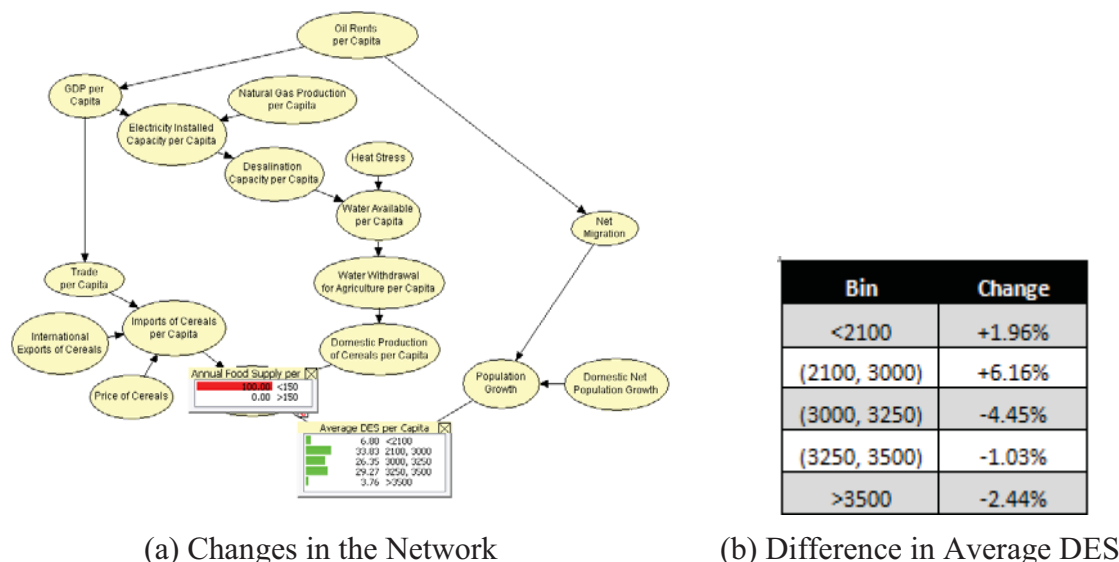


Figure 33. Change in Probability Distribution During an Attack on Strategic Storage Sites

Of the five scenarios explored in this study, the two greatest threats appear to come from an attack on strategic storage sites, which would drastically decrease Oman's annual food supply, and an international refusal to sell crops, which would also indirectly diminish annual food supply. These two crises produced clear, one-directional movement towards more food insecure probability distributions in average Daily Energy Supply.

It should come as no surprise that these two crises displayed the greatest sensitivity to food security, as they represent a particularly direct and immediate impact to food supply, whereas the other crises may affect food security over time. Regardless, this student took an important step in allowing the quantification of sensitivity for average DES.

VI. The Most Food Insecure and Food Secure Outcomes

The crisis testing demonstrated how different scenarios impact the probability distribution for average DES. In observing shifts in this distribution, it is worthwhile to note how to fix the other seventeen nodes to make the lowest state of average DES have its highest probability, representing the most food insecure outcome. On the other hand, the same test can be performed to maximize food security by giving the highest state of average DES its highest probability. These experiments were performed with the Hugin Educational 8.0 software's Max Propagation Tool, which shows which states belong to the most likely combination of states for a specific outcome; each node's state with a value of 100.00 is the most likely.¹¹⁴

Figure 34 shows the combination of states that are most likely to occur when average DES is in its most food insecure state of less than 2100 kilocalories/person/day. All five of the Energy nodes were fixed to their highest states, along with the trade per capita node. The middle state for the net migration node in the Human Factors cluster was most likely, along with the highest states for domestic net population growth and population growth. Looking exclusively at

¹¹⁴ Hugin Help Pages, "How to Build a Bayesian Network," Bayesian Networks Tutorial, http://download.hugin.com/webdocs/manuals/Htmlhelp/bn_tu_pane.html (accessed February 9, 2015).

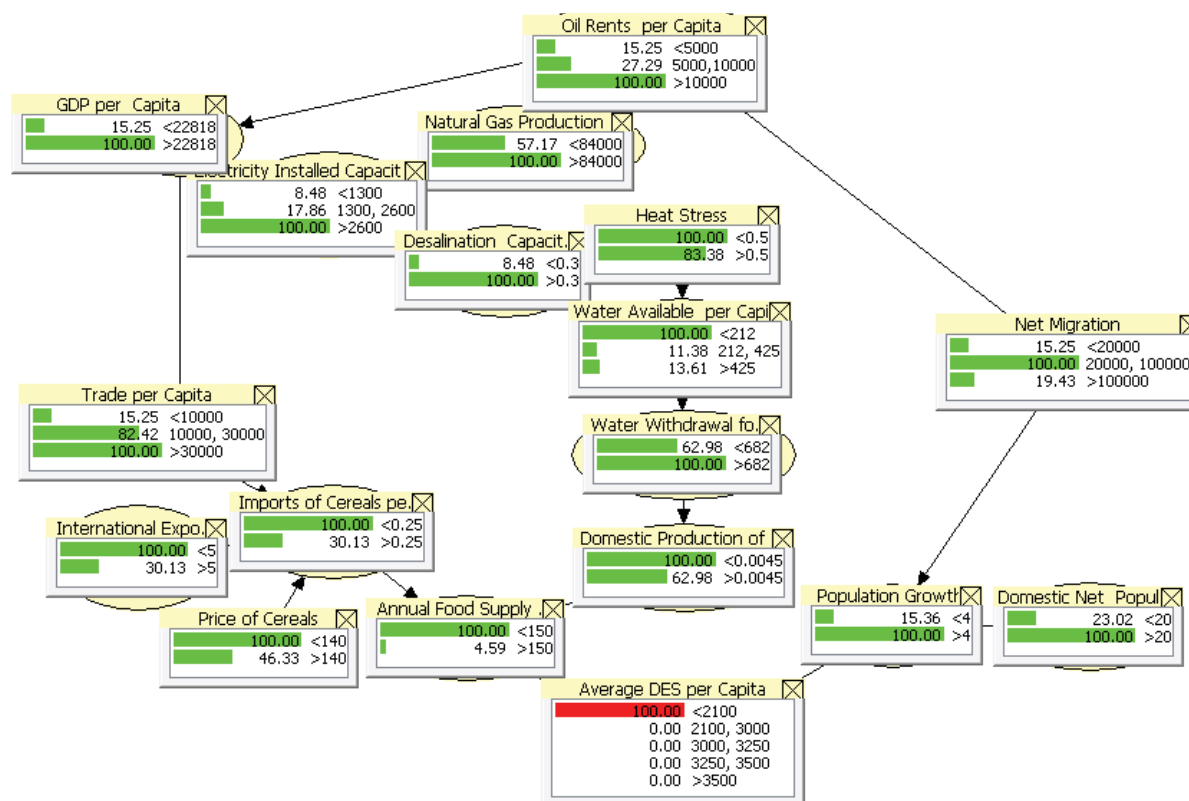


Figure 34. The Most Food Insecure Outcome

these nodes, the most food insecure scenario seems to have a robust economy and energy production, encouraging fairly high net migration into the Arabian Gulf and not dissuading domestic families from having children. Aside from trade per capita, though, the international exports, imports of cereals, imports of cereals per capita, and annual food supply per capita nodes were all fixed to their lowest states. Similar to the two supply-related crises tested above, the attack on strategic storage sites and international refusal to sell crops, the most food insecure scenario demonstrates low availability of cereals, and in this case, the high population growth aggravates the situation. The Domestic Agriculture variables vary in being fixed to their low and high states. As with the drought scenario above, it appears that having low water availability, high water withdrawal, and low domestic production, while unfortunate for the Arabian Gulf, is not the most critical element in undermining Oman's food security. Given the crises tested above and the 2008 availability crisis, the Trade variables appear most impactful.

Figure 35 displays the combination of states that produces the most food secure outcome for Oman, as represented in the highest bin for average DES of greater than 3500 kilocalories/person/day. As with the most food insecure combination, all five of the Energy variables and the trade per capita node were fixed to their highest states. Furthermore, net migration and the population growth variables were the same, indicating the presence of a strong economy and a lack of reservations about having big families. Somewhat surprisingly, though, international exports of cereals and imports of cereals per capita remained in their lower states. Annual food supply, as expected, shifted to its highest state, but domestic production of cereals also shifted to its highest state. In this scenario then, it appears that the nation compensates for low cereal imports by producing domestically, also managing to use efficient agricultural

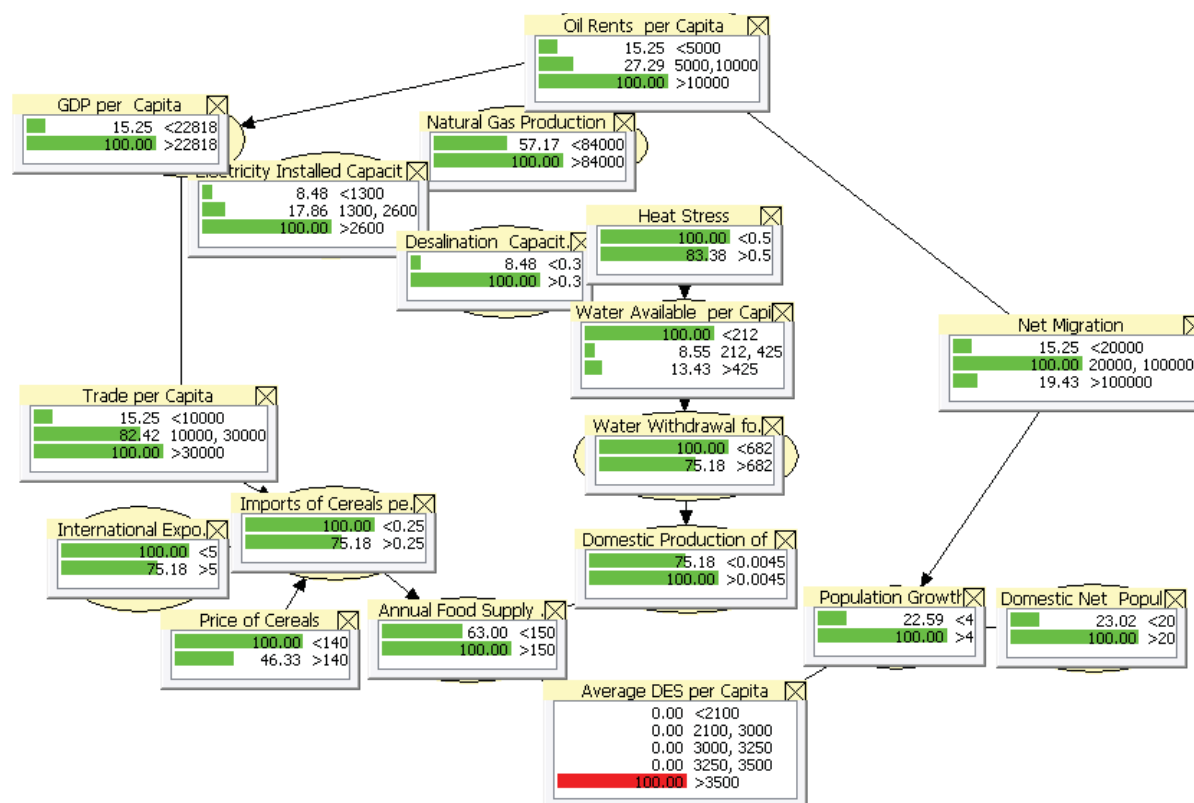


Figure 35. The Most Food Secure Outcome

practices by keeping water withdrawal for agriculture per capita in its lowest state. Because Oman currently imports 80% of its food supply, this scenario appears unrealistic to implement in the short-run.¹¹⁵ Regardless of compensating domestically or securing international trade lines, the importance still lies in ensuring a high annual food supply for Oman, corroborated in the crisis scenarios.

Both the most food insecure and the food secure scenarios best compared to Oman's actual environment between 1988 and 2000. As shown in the World Bank datasets, Oman had high domestic net population and high population growth during those years, not shifting to the lower states of these variables until 2001. In 1988, too, Oman's energy industry also began to expand, as the natural gas production per capita shifted to its higher state. At the same time, international exports of cereals remained low.¹¹⁶ During that time, Oman was vulnerable to its most food insecure situation, but it also had the potential to increase the probability distribution of higher states of average DES. Luckily, it appears that Oman has moved towards more security in the twenty-first century by curbing its domestic net population growth and taking advantage of the higher levels of international exports of cereals. Further recommendations to increase food security, though, are included in the next section.

¹¹⁵ Food and Agriculture Organization of the United Nations, "Food Imports by Oman Set to Grow to \$4.8bn."

¹¹⁶ The World Bank, "Oman: Data"

VII. Policy Recommendations and Future Endeavors

Arabian Gulf nations like Oman need to reduce food insecurity in order to combat the associated national security risks. To keep pace with population growth, one potential strategy focuses on domestic agricultural-productivity growth; Oman must account for increasing diversion to biofuel production and rising food consumption in India, China, and other developing nations. The World Bank suggests that a 1% increase in agricultural growth can reduce poverty by 2%.¹¹⁷ New farming technologies can increase yields in the Arabian Gulf, despite trends pushing renewable water below 500 cubic meters per capita by 2050. With average rates of agricultural return at 36% for Middle Eastern countries, funding for agricultural research and techniques, like hydroponic farming in Salalah, could increase, rather than maintain a current trend of less funding than other regions. Although importation will remain an essential part of food security, Gulf nations can invest in transportation, marketing, and production since these comprise 75% of retail food prices.¹¹⁸ While investment and development could assist Arabian Gulf nations, these countries must account for their costs if they become part of their food security strategies.

In the short run, though, Oman should work on securing its import-reliant food supply through storage of international sources and a budding fishing industry. To this end, Oman has built a 200,000 ton-capacity wheat silo at Sohar, a 140,000 ton-capacity silo at Salalah, and a 120,000 ton-capacity barley and grains silo in Muscat, and the nation should continue building state-of-the-art wheat storage facilities at major ports; this initiative fosters price stability, maintains adequate wheat for any unforeseen crisis up to nine months, and minimizes risk by diversifying the location of the grains.¹¹⁹ Recognizing the importance of seafood products in strategic storage, too, the Ministry of Agriculture of Fisheries has allocated OMR 500 million, or over \$1.5 billion, to develop the fishing sector between 2013 and 2020, focusing on the fish processing complex in Duqm and infrastructure development like electricity, internal roads, and water networks for 60 land plots for aqua farming. At the end of 2020, Oman anticipates having raised its fish production from the sea and aqua farms from 210,000 tons to 500,000 tons.¹²⁰ Strategic storage, bolstered by the seafood products industry, supplements and protects Oman's import-heavy annual food supply.

Aside from the food supply, Oman should pay particular attention to obesity and malnutrition issues, too. Food security involves a healthy population as much as an adequate supply of food. A significant proportion of children are undernourished in the Arabian Gulf, as a third of the population in Oman—including the blue-collar expatriate workers—suffers from micronutrient deficiencies. Seemingly paradoxically, non-communicable diet-related diseases like obesity, heart disease, diabetes, and cancer have dominated public health issues among adults. In the United Arab Emirates, for instance, 66% of men and 60% of women are

¹¹⁷ Luc Christiaensen, Lionel Demery, and Jesper Kuhl, "The Role of Agriculture in Poverty Reduction: An Empirical Study," *World Bank Policy Research Working Paper 4013* (2006), <http://elibrary.worldbank.org/doi/pdf/10.1596/1813-9450-4013> (accessed December 03).

¹¹⁸ Qatar National Food Security Programme, "The Global Food Crisis: Middle Eastern Dimension."

¹¹⁹ "Boosts to Food Storage in Oman," *Business Today*, November 1, 2014, www.businesstoday.co.om/issues/flight-plan/boost-to-food-storage-in-Oman (accessed February 1, 2015).

¹²⁰ ONA, "Ministry Allocates OMR500 Million for Fisheries Development," *Times of Oman*, March 20, 2015, <http://www.timesofoman.com/News/49144/Article-Ministry-allocates-OMR500-million-for-fisheries-development> (accessed March 20, 2015).

overweight or obese, and other Arabian Gulf nations like Oman have similarly high rates.¹²¹ The presence of both malnutrition and obesity indicates a lack of dietary education and unhealthy cultural norms. As this Trident project can potentially serve as a tool for re-education and strategic planning, part of this re-education should focus on the consumption of nutritious, diversified kilocalories in the average DES. The nutritional aspect of food security is a potential area of future study.

VIII. Conclusions

After testing different scenarios, the changes in probability distribution for average DES revealed trends that help distinguish the sensitivity of the final node to the different categories of variables. These patterns demonstrate the correctness of the hypothesis that the Trade category would trigger the most variability in the probability distribution for average DES.

The Trade variables proved most sensitive to change because they produce the most one-directional movement in the probability distribution towards food insecurity; the lowest and second-lowest bins for average DES increased in probability, while the three bins with the highest average DES decreased. Oman's heavy reliance on imports for its food supply helps explain the sensitivity of the Trade variables. To reduce the impact of changes in Trade variables, Oman should consider increasing its food storage capacity and developing its domestic fishing industry.

The Domestic Agriculture variables proved least sensitive to change because they produce little variability in the probability distribution for average DES. The Arabian Gulf is accustomed to arid, water-scarce conditions, therefore reducing the shock value of an agricultural crisis. With these minimal effects, Oman should consider allocating limited water resources away from agriculture and developing alternative agricultural practices, like hydroponic farming. Wastefulness prevails in the current agricultural culture due to the high consumption of water resources with little addition to the food supply.

The Energy and Human Factors variables produce inconclusive results, largely due to the net migration node and the dampening effect of propagation through the Domestic Agriculture variables. The net migration node especially demonstrates the limitation of a Bayesian belief network in reconciling short-term and long-term effects; in the short-run, a low net migration means a lower population and higher average DES, but in the long-run, the economy will suffer from a lack of low-wage workers and the loss of income they spend in Oman, resulting in a lower food supply and lower average DES. Similarly, reverse causality can also result in a good economy attracting expatriate workers and high net migration. In this study, the inconclusive results may suggest that Oman's biggest fear should be the unknown results, particularly with the Human Factors variables.

Future endeavors for this project could focus on addressing some of the underlying issues of Bayesian belief networks. With a very supply-centric approach to food security, this project could expand in the future by focusing on the nutritional aspect of food security; the Arabian Gulf countries have alarming obesity and malnutrition levels, indicating the need for more than just kilocalories per person per day; the calories should be well-balanced and nutritional, and it would be interesting to explore how that criterion changes the food security environment.

¹²¹ Abdulrahman Musaiger, Abdelmonem Hassan, and Omar Obeid, "The Paradox of Nutrition-Related Diseases in the Arab Countries: The Need for Action," U.S. National Library of Medicine, September 8, 2011, <http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3194109/> (accessed November 10, 2013).

Because this project's network contains data from as far back as 1970, the question arises of the relevance of the "old" data to Oman's food security environment today. To this end, it would be interesting to observe in the future if Oman ever returns to the states of variables that dominated the 1970s and 1980s. In regards to observing short-term versus long-term effects, the Bayesian belief network accounts for year-to-year changes, but perhaps the datasets could be manipulated to reflect the long-term effects of crises, especially in regards to potential human population shifts. Because binning is a subjective, major limitation to all Bayesian belief networks, it would be an interesting endeavor to see how to change the split points for the states to minimize the number of "bad" years, where the probability of the actual state for average DES for that year decreases. Lastly, this project would benefit from orders of magnitude of more data, so the Bayesian belief network could potential expand to a global focus, or the methodology could be applied to an entire different social science problem.

Above all else, this Trident project's methodologies are of key importance. By quantifying sensitivity to average DES, this project takes some of the initial steps in bringing measurable, calculated threat assessment into food and national security policy. Whether highlighting immediate security vulnerabilities in the region that houses the United States Navy's Fifth Fleet or modeling other social science problems in the future, the Bayesian belief network can serve as a valuable tool for re-education and policy recommendations.

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X. Human Research Protection Program Approvals



*U.S. Naval Academy Human Research Protection Program
Nimitz Library G10 - Mail Stop 10M - Annapolis, Maryland 21402*

30 January 2014

MEMORANDUM

From: Ms. Erin Johnson, USNA HRPP Office
To: MIDN 2/C Andrea Howard, Political Science Department
Subj: APPROVAL OF HUMAN SUBJECT RESEARCH AMENDMENT
Ref: (a) SECNAVINST 3900.39D
(b) 32 CFR 219
(c) USNA HRPP Policy Manual

USNA Assurance # DoD N-40052

HRPP Approval # **USNA.2014.0003-IR-EM3-A**

1. The Superintendent, as the Institutional Official (IO), reviewed and approved your research protocol "Oman's Unique Food Security Outlook" involving human subjects. The co-investigators are Assoc Prof Deborah Wheeler, Asst Prof Michael Kellerman (both from the Department of Political Science), and Prof Richard Crabbe from the Department of Computer Science. The protocol was determined to be exempt under 32 CFR 219.101(b)(3).
2. The purpose of this research is to define Oman's food security strategy and use data collected to generate a model that can predict Oman's food and water needs for the next ten years. Data collection will derive mostly from primary sources and the research population will solely consist of public officials.
3. Research which is determined to be exempt under 32 CFR 219.101 is exempt from all regulatory requirements, unless there is a substantive change that could potentially alter the assessment of the exempt status. If there is a substantive change you must submit an amendment to your protocol in sufficient time to process the revisions and secure approval from the Superintendent. On an annual basis, a status update of all exempt studies will be conducted.
4. When the research has concluded, notify the USNA HRPP Office. In accordance with Section XIII of the USNA HRPP Policy and Procedures manual, provide this office with copies of any articles or presentations resulting from this research. Additionally, any presentations or publications must include acknowledgement of IRB approval using the HRPP approval number.
5. If you have any questions, please contact this office at 410-293-2533 or HRPPoffice@usna.edu.

ERIN JOHNSON
USNA HRPP Office



DEPARTMENT OF THE NAVY
UNITED STATES NAVAL ACADEMY
121 BLAKE ROAD
ANNAPOLIS MARYLAND 21402-1300

3900
23 January 2014

MEMORANDUM

From: Chair, Institutional Review Board (Code 28)
To: Superintendent, United States Naval Academy

Subj: HUMAN SUBJECT RESEARCH BY MIDN 2/C ANDREA HOWARD (POLITICAL SCIENCE DEPARTMENT)

Ref: (a) SECNAVINST 3900.39D
(b) 32 CFR 219
(c) USNA HRPP Policy Manual

Encl: (1) Protocol Package for MIDN 2/C Andrea Howard (Forms 1, 3, 4, 5, 5-A, CITI, and Supplemental Information)

1. I have reviewed the research protocol submitted by MIDN 2/C Andrea Howard from the Political Science Department on "Oman's Unique Food Security Outlook." Co-investigators are Assoc Prof Deborah Wheeler, Asst Prof Michael Kellerman (both from the Department of Political Science), and Prof Richard Crabbe from the Department of Computer Science.
2. The purpose of this research is to define Oman's food security strategy and use data collected to generate a model that can predict Oman's food and water needs for the next ten years. The model can then be applied to different nations to determine its accuracy in other environments. The data collection will derive mostly from primary sources found and interviews collected with public officials in both Oman and the United States. Informed Consent and interview questions are included in Supplemental Information.
3. This research is determined to be exempt under 32 CFR 219.101(b)(3). Research which is determined to be exempt under 32 CFR 219.101 is exempt from all regulatory requirements. If there is a substantive change that could potentially alter the assessment of the exempt status, then please contact the USNA HRPP Office. On an annual basis, a status update of all exempt studies will be conducted.


RICHARD O'BRIEN

27 Jan 14


Date: 1-29-14

☒ Approved

☐ Modification

☐ Disapproved

Comments:


M. H. MILLER
Vice Admiral, U.S. Navy
Superintendent

XI. Appendix I: Challenges with the Project

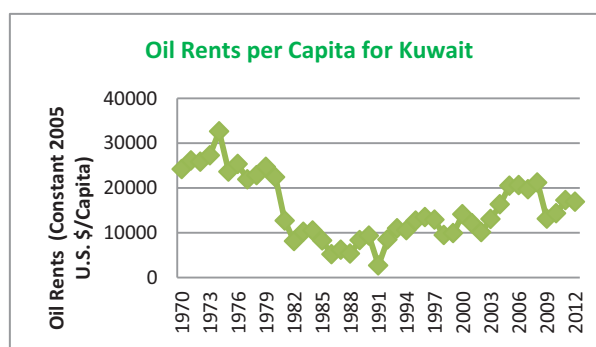
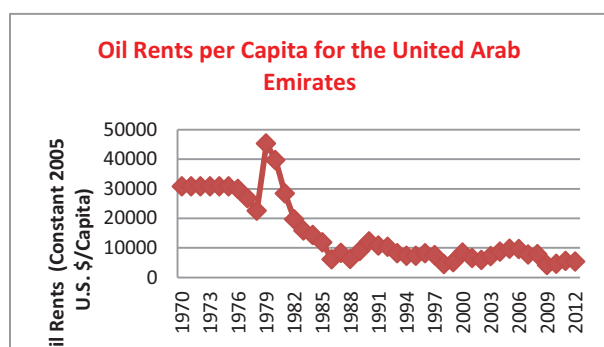
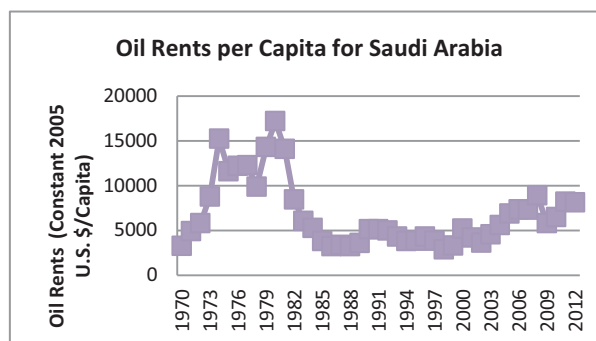
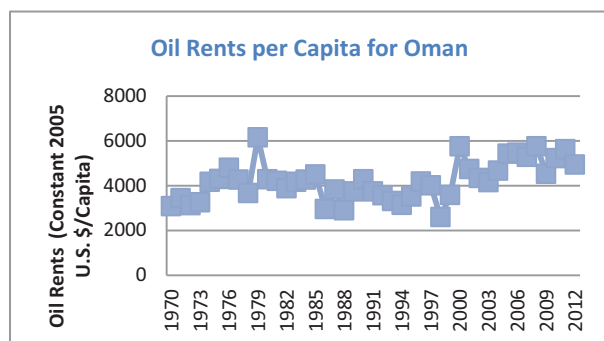
When constructing the Bayesian belief network, a number of challenges arose:

1. The first obstacle was to determine what software to use for constructing the Bayesian belief network. Initially, I considered utilizing Norsys Software Corporation's Netica program, but the Hugin Lite 8.0 trial possessed more capabilities. In addition to employing typical discrete chance nodes, this program also had a Max Propagation Tool.
2. When using the Hugin Lite 8.0 software, I exceeded the trial version's limit of fifty bins per network. In order to extend the network to its appropriate size, I purchased and upgraded to the Hugin Educational 8.0 software. This version of the program allows networks of any size.
3. When constructing the network, the next challenge involved converting the data for each variable in a sub-group of nodes into a conditional probability for that entire sub-group. Initially, if a two-node sub-group had variables with two states each, I would manually go through the two data sets to determine which years had the low outcome for both variables, a low bin and a high bin, or both high bins. This process of manually sorting the data into the four possible combinations of bins proved extremely time-consuming, and the process became much more difficult when the number of nodes in each sub-group, as well as the number of states per variable, increased. To solve this issue and make the counting more efficient, I worked with Professor Crabbe to develop a computer program in the Python language; the program digitally completed the same counting method I had employed with matrices, and it then divided each combination's count by the sum of the counts. The division produced the conditional probability for each combination of the sub-group variables' states.
4. Once the datasets for Oman, the United Arab Emirates, Saudi Arabia, and Kuwait were assembled, the question arose of how to bin the datasets for each node. While we explored the idea of optimizing the distribution of the data points between the bins, we realized that this approach was not ideal for this study; instead, a better option involved using states that had some significance for the current social setting. The binning was still subjective, though.

XII. Appendix II: Graphs for the Variables

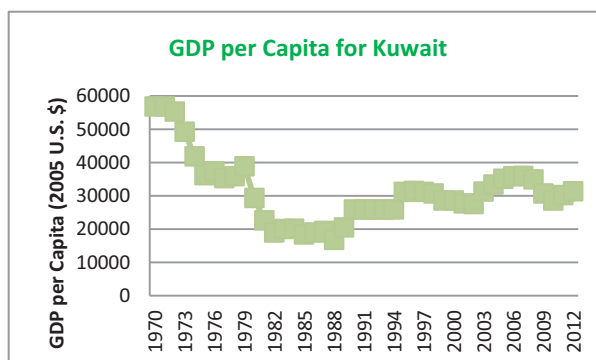
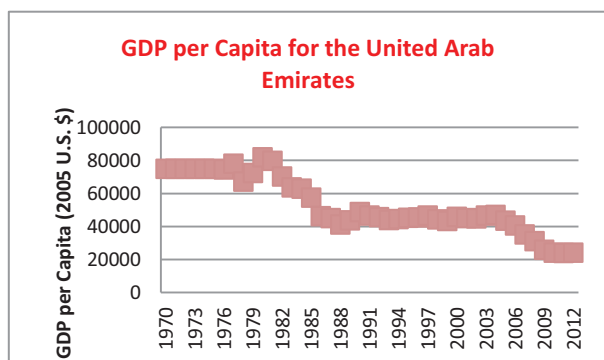
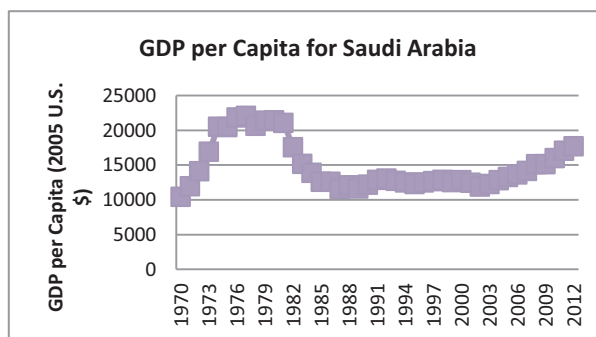
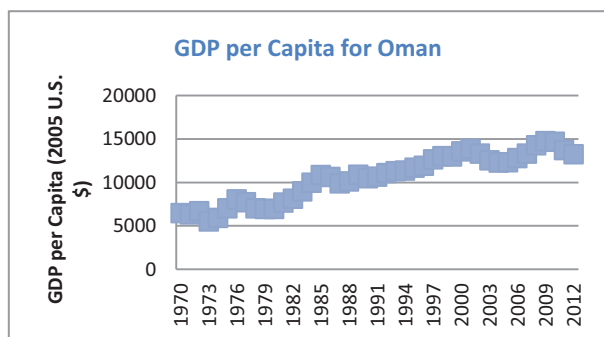
Oil Rents per Capita (Constant 2005 U.S. Dollars per Capita) – 172 Cases

Source: The World Bank



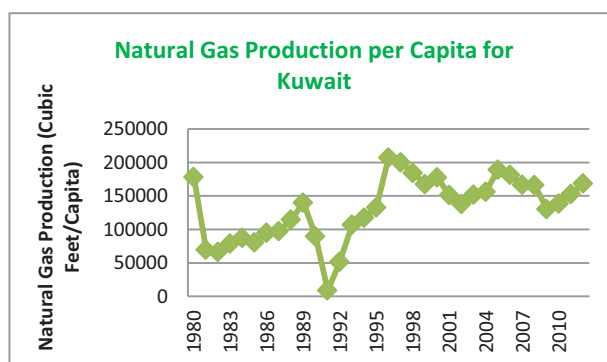
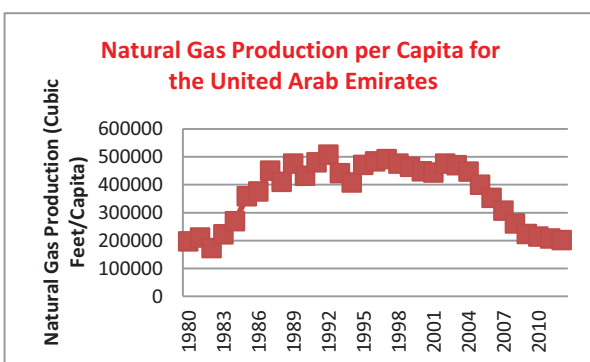
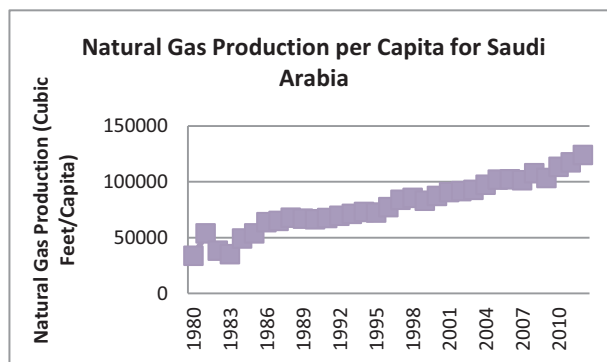
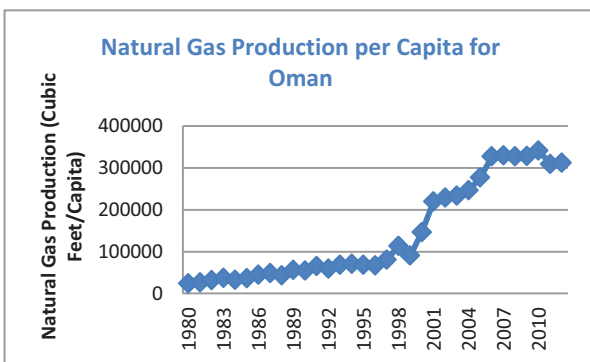
GDP per Capita (Constant 2005 U.S. Dollars per Capita) – 172 Cases

Source: The World Bank



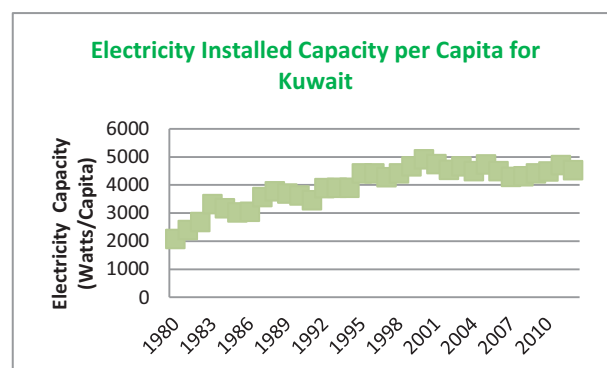
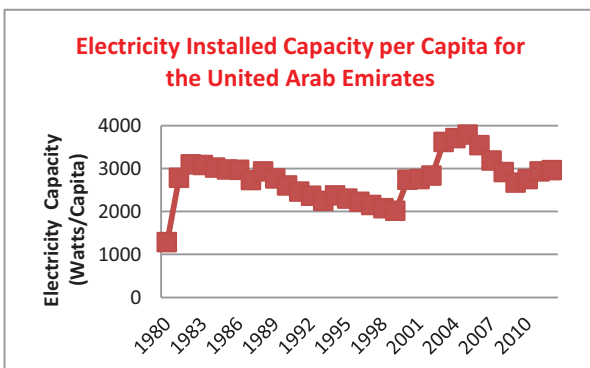
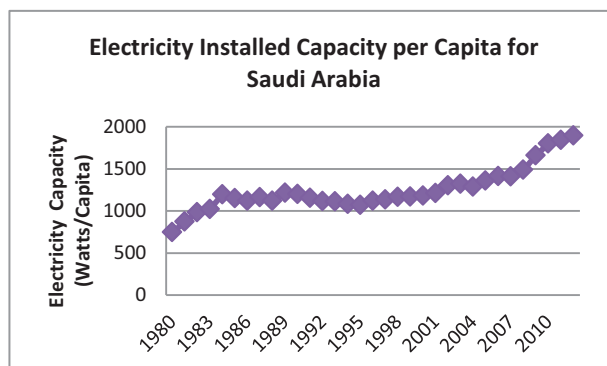
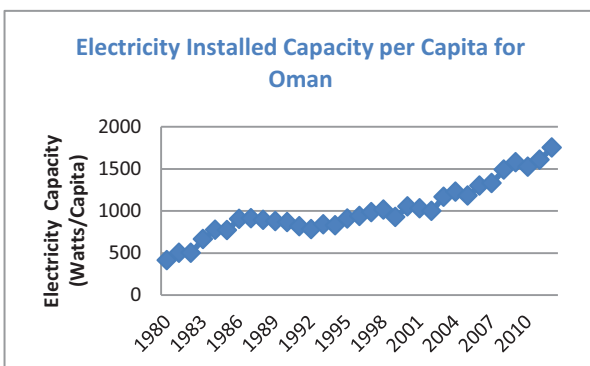
Natural Gas Production per Capita (Cubic Feet per Capita) – 132 Cases

Source: U.S. Energy Information Administration



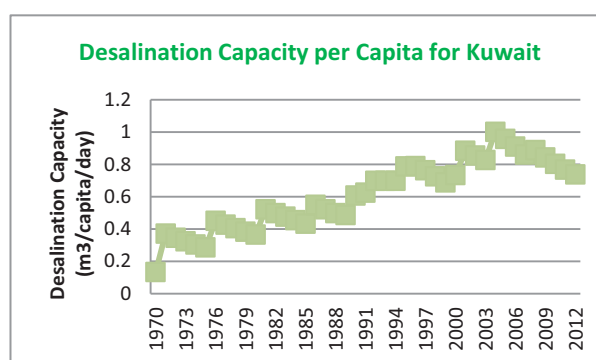
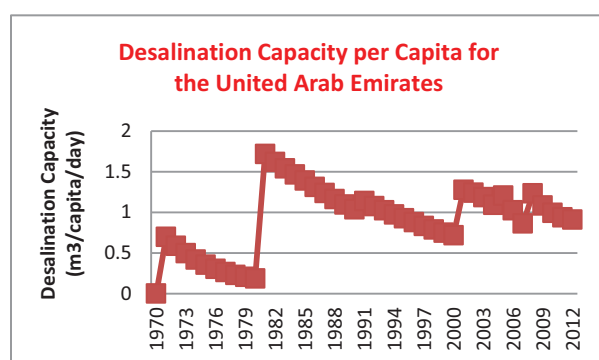
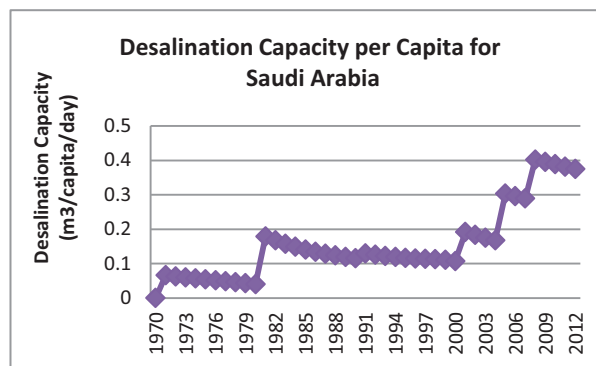
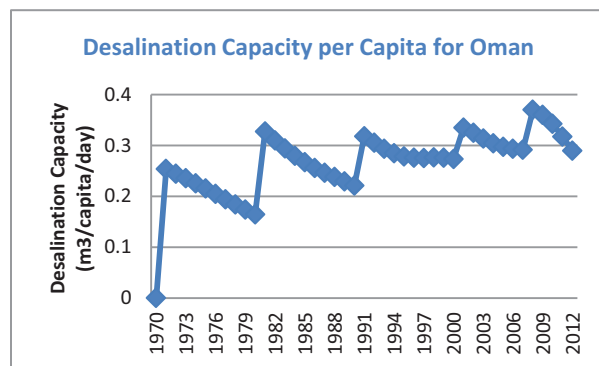
Electricity Installed Capacity per Capita (Watts per Capita) – 132 Cases

Source: U.S. Energy Information Administration



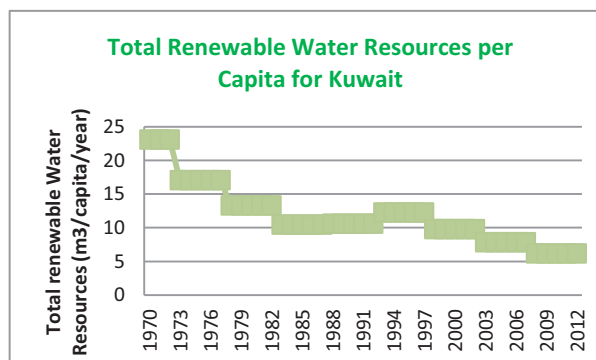
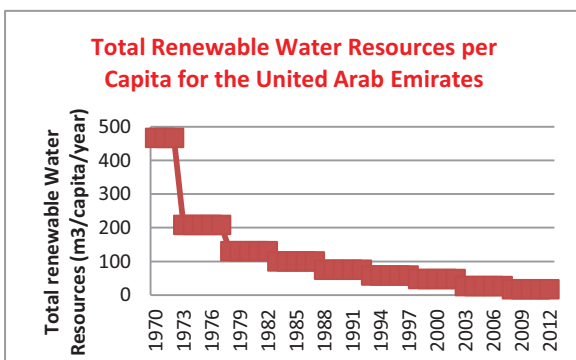
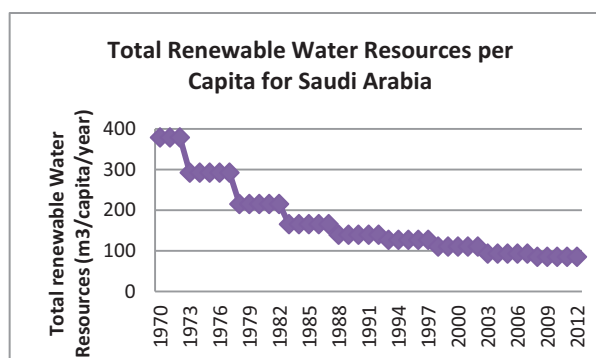
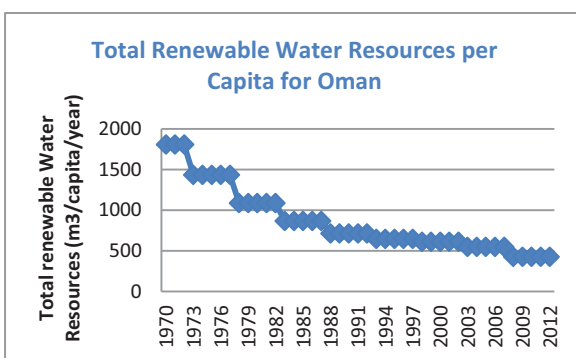
Desalination Capacity per Capita (Cubic Meters per Capita per Day) – 172 Cases

Source: ESCWA Water Development Report



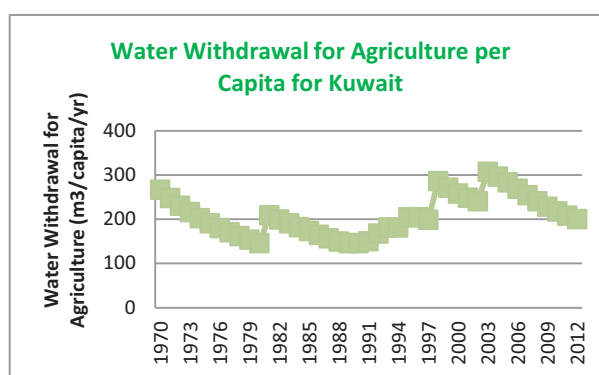
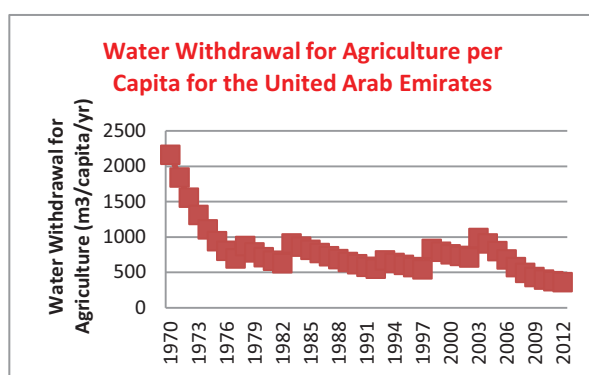
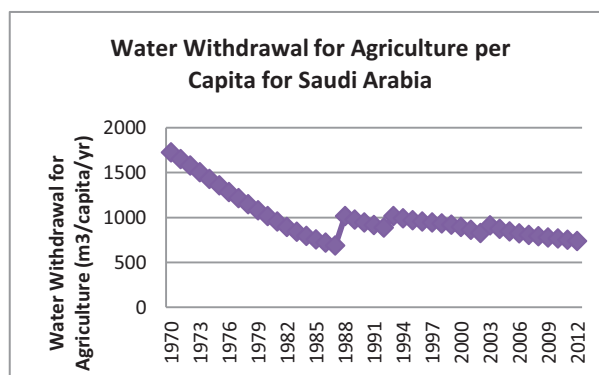
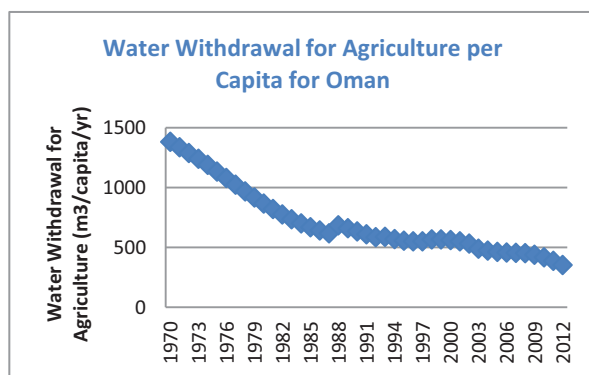
Water Available per Capita (Cubic Meters per Capita per Year) – 172 Cases

Source: AquaStat



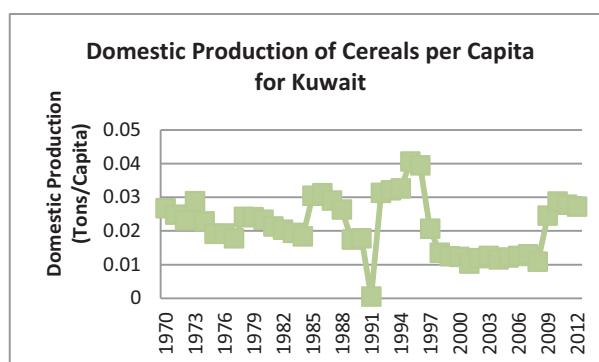
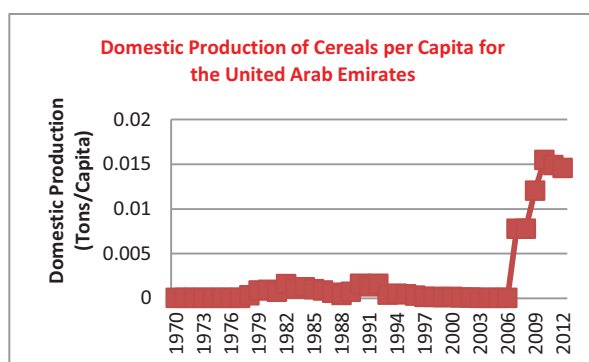
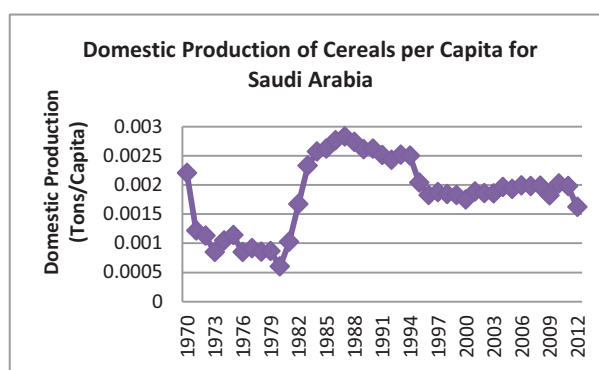
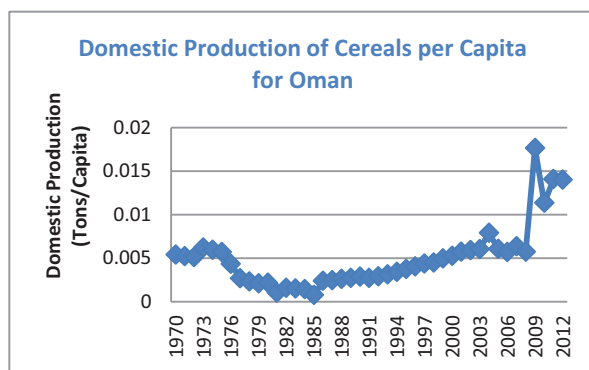
Water Withdrawal for Agriculture per Capita (Cubic Meters per Capita per Year) – 172 Cases

Source: AquaStat



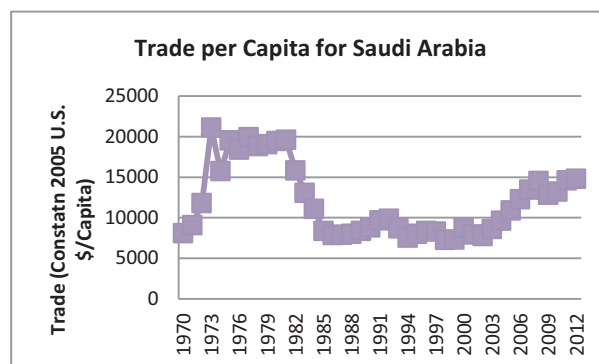
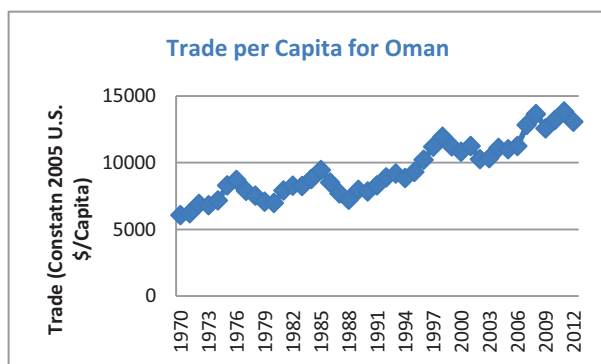
Domestic Production of Cereals per Capita (Tons per Capita per Year) – 172 Cases

Source: FAOSTAT



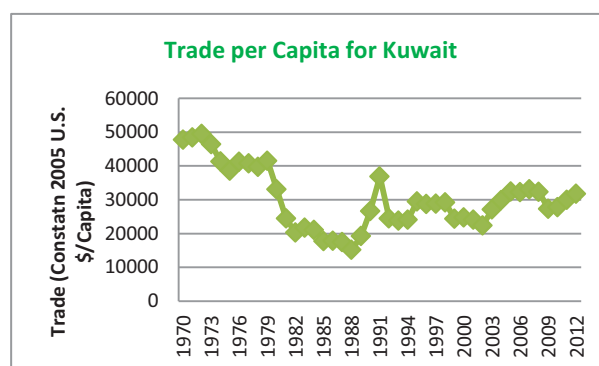
Trade per Capita (Constant 2005 U.S. Dollars per Capita) – 129 Cases

Source: The World Bank



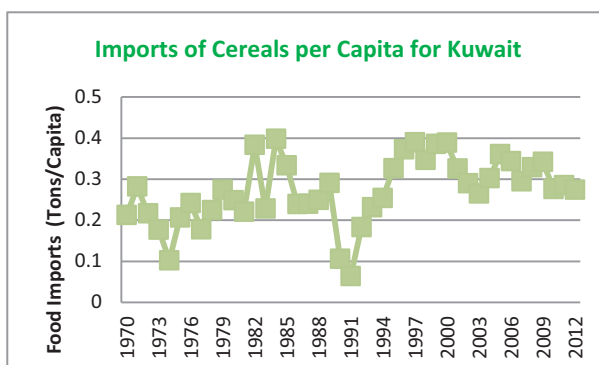
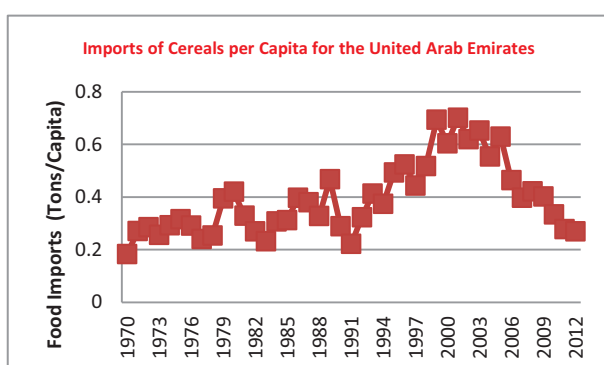
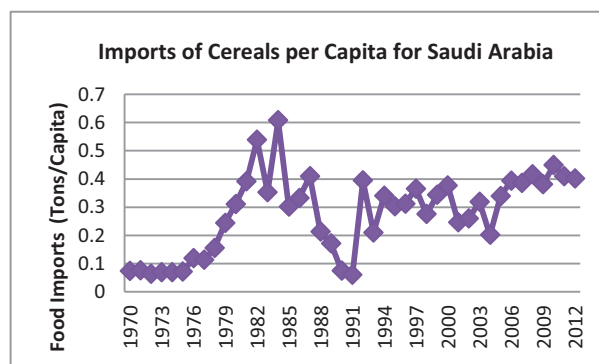
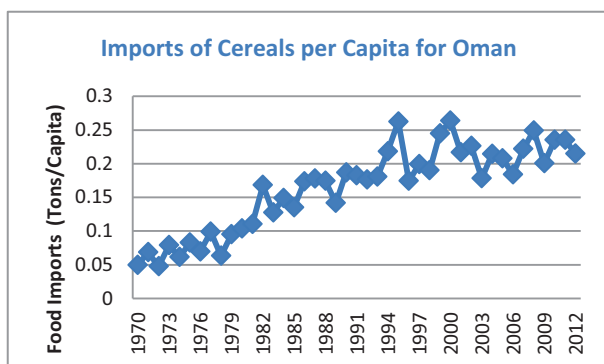
United Arab Emirates

Not Available



Imports of Cereals per Capita (Tons per Capita) – 172 Cases

Source: FAOSTAT



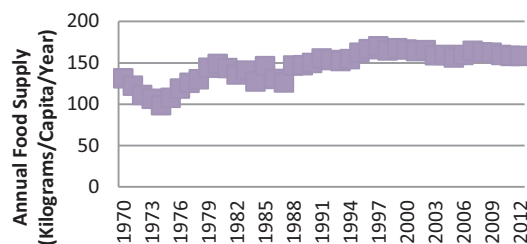
Annual Food Supply (Kilograms per Capita per Year) – 129 Cases

Source: FAOSTAT

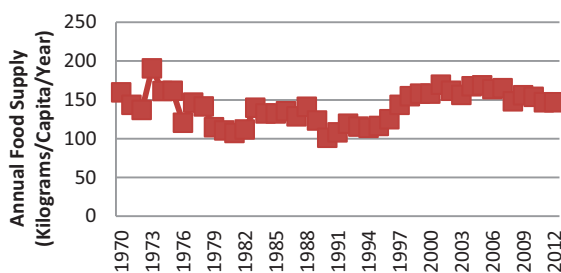
Oman

Not Available

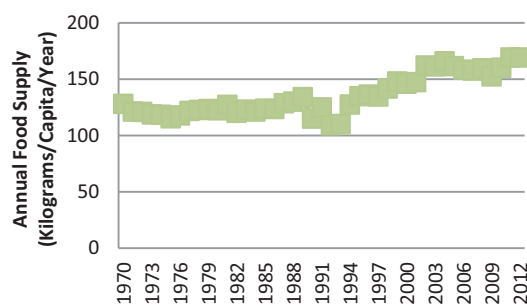
Annual Food Supply for Saudi Arabia



Annual Food Supply for the United Arab Emirates



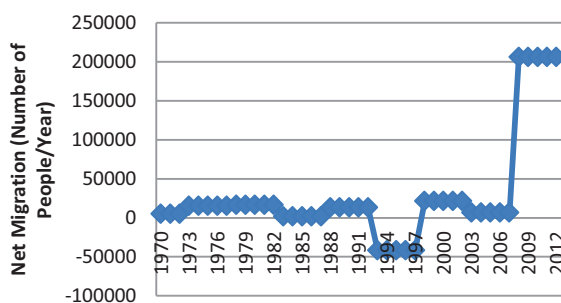
Annual Food Supply for Kuwait



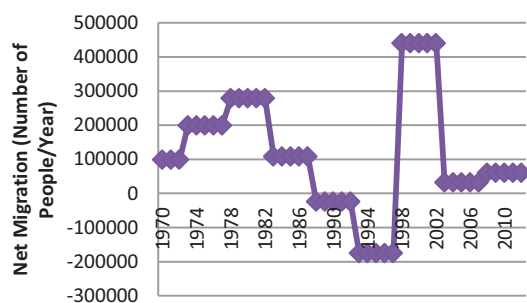
Net Migration (People per Year) – 172 Cases

Source: The World Bank

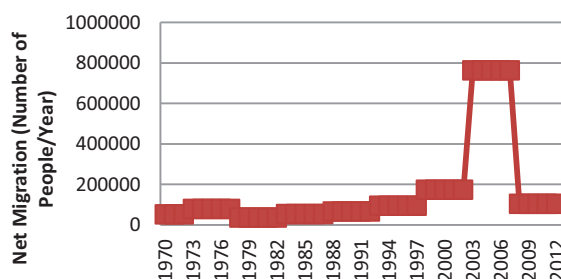
Net Migration for Oman



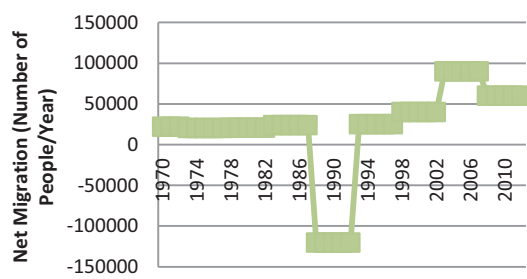
Net Migration for Saudi Arabia



Net Migration for the United Arab Emirates

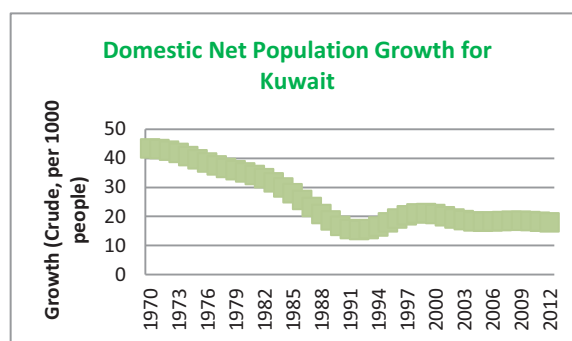
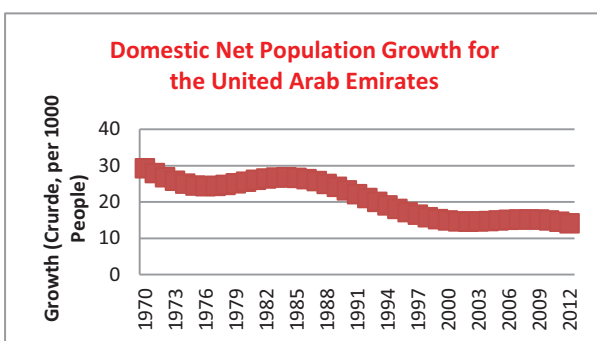
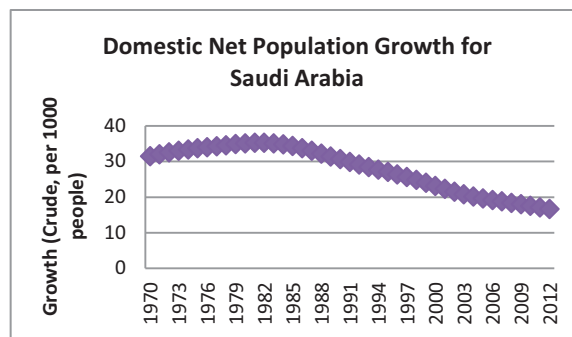
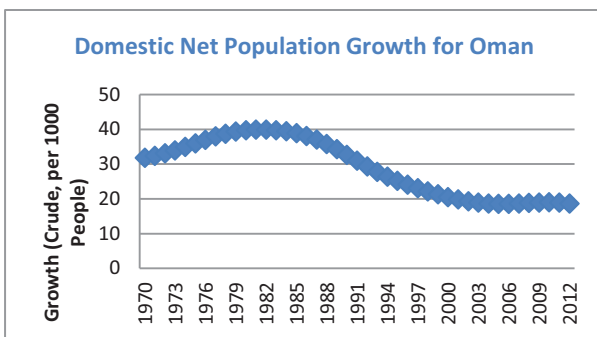


Net Migration for Kuwait



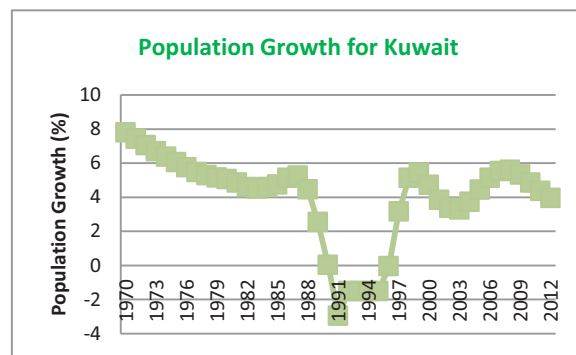
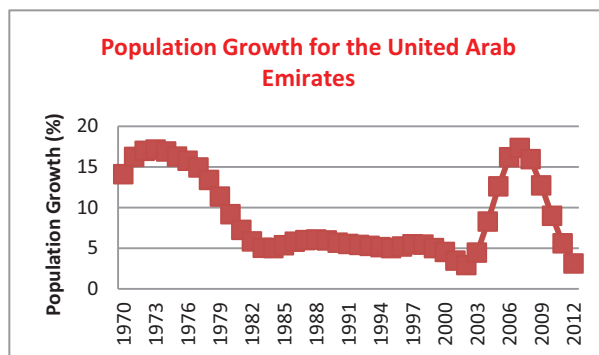
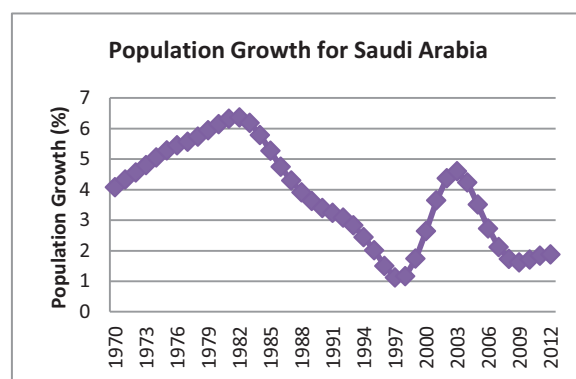
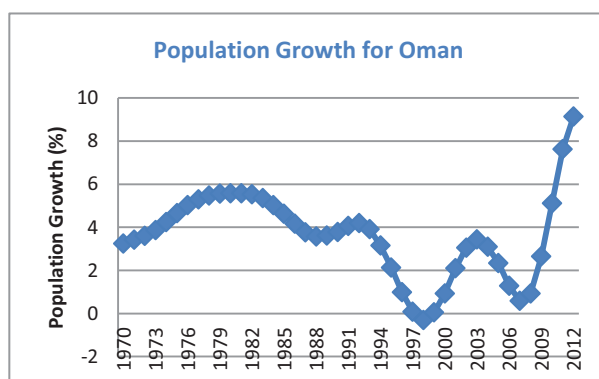
Domestic Net Population Growth (per 1,000 People) – 172 Cases

Source: The World Bank



Population Growth (Percentile) – 172 Cases

Source: The World Bank



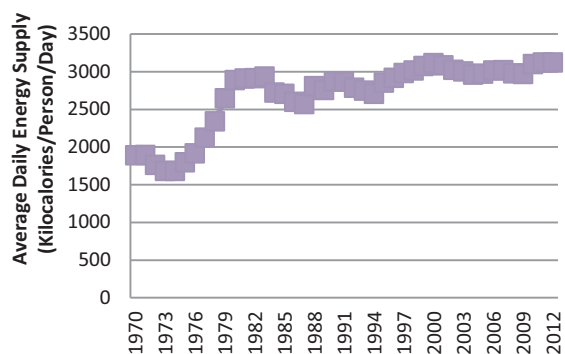
Average Daily Energy Supply (Kilocalories per Person per Day) – 132 Cases

Source: FAOSTAT

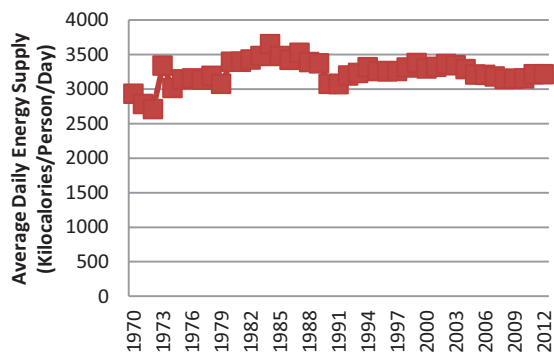
Oman

Not Available

Average Daily Energy Supply for Saudi Arabia



Average Daily Energy Supply for the United Arab Emirates



Average Daily Energy Supply for Kuwait

